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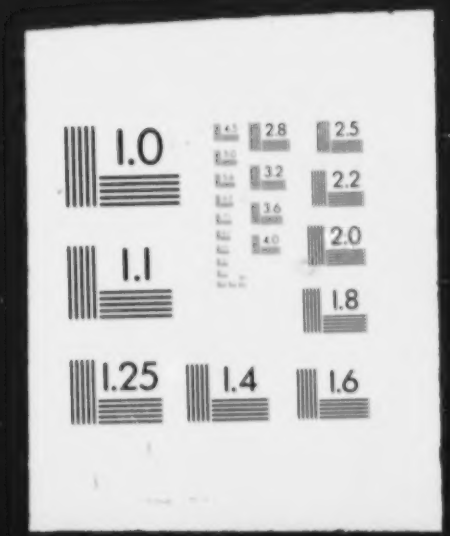

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Reductions of Enteric Microorganisms during Aerobic Sludge Digestion Comparison of Conventional and Autoheated Digesters

Cornell Univ., Ithaca, NY

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The objectives of this investigation were to: (1) determine the seasonal variations in sludge stabilization and reductions in the densities of indicator organisms, Salmonella ssp., and enteroviruses that occur with conventional aerobic digestion in cold climates, and (2) demonstrate that both sludge stabilization and reductions in the densities of these microorganisms can be improved by simple modifications that increase process temperature. Two 32 m^3 aerobic digesters located at a small municipal wastewater treatment plant were operated continuously over a period of 20 mo to obtain the data necessary to satisfy these objectives. One digester was a conventional digester while the other was designed to minimize heat losses and thus, facilitate autoheating.

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REDUCTIONS OF ENTERIC MICROORGANISMS DURING AEROBIC SLUDGE DIGESTION: COMPARISON OF CONVENTIONAL AND AUTOHEATED DIGESTERS

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U. S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report contains data on an evaluation of aerobic municipal wastewater sludge digestion, a commonly used alternative for sludge treatment. The objectives of this investigation were to: (1) determine the seasonal variations in sludge stabilization and reductions in the densities of indicator organisms, Salmonella spp., and enteroviruses that occur with conventional aerobic digestion in cold climates, and (2) demonstrate that both sludge stabilization and reductions in the densities of these microorganisms can be improved by simple modifications that increase process temperature. Two 32 m^3 aerobic digesters located at a small municipal wastewater treatment plant were operated continuously over a period of 20 months to obtain the data necessary to satisfy these objectives. One digester was a conventional digester while the other was designed to minimize heat losses and thus, facilitate autoheating. Significant improvements were seen when heat losses were minimized.

E. Timothy Oppelt, Acting Director
Risk Reduction Engineering Laboratory

ABSTRACT

The objectives of this investigation were to: (1) determine the seasonal variations in sludge stabilization and reductions in the densities of indicator organisms, Salmonella spp., and enteroviruses that occur with conventional aerobic digestion in cold climates, and (2) demonstrate that both sludge stabilization and reductions in the densities of these microorganisms can be improved by simple modifications that increase process temperature. Two 32 m^3 aerobic digesters located at a small municipal wastewater treatment plant were operated continuously over a period of 20 months to obtain the data necessary to satisfy these objectives. One digester was a conventional digester while the other was designed to minimize heat losses and thus, facilitate autoheating.

Conventional digester mixed liquor temperatures at the constant residence time of 20 days ranged from a minimum of 8 °C to a maximum of 26 °C over the 20 months of operation. In contrast, the range of autoheated digester mixed liquor temperatures for residence times of 10, 15, and 20 days was substantially higher, 29 °C to 40 °C, even with relatively dilute sludges.

When the results from the two digesters, eleven separate periods of steady-state operation, were combined, strong linear relationships were observed between the rate of $\log_{10}$ reductions and the reciprocal of mixed liquor temperature for each of the three groups of indicator organisms and also for the enterovirus group of viruses. Enteroviruses were found to be most sensitive to the effect of temperature increases while fecal streptococci were the most resistant. Unfortunately, the absence of consistently detectable numbers of Salmonella spp. in the raw sludge used in this study precluded any determination of the effects of mixed liquor temperature and residence time on the reduction of this group of microorganisms during aerobic digestion.

No strong linear relationships were observed between first-order reaction rate coefficients for three of the parameters used to characterize sludge stabilization; total volatile solids, chemical oxygen demand, and organic nitrogen; and mixed liquor temperature. However, when first-order reaction rate coefficients for total volatile solids and chemical oxygen demand calculated from the results obtained in this study were combined with reaction rate coefficients calculated from results reported by other investigators to extend the range of data, strong linear relationships between these reaction rate coefficients and mixed liquor temperature were observed and defined mathematically.

When residence times necessary to provide a 38 percent reduction in total volatile solids concentration are compared to residence times necessary to realize a two $\log_{10}$ reduction in indicator organisms and enteroviruses for mixed liquor temperatures up to 40 °C, residence time for microbial rather than volatile solids reductions appeared to be the critical design parameter for aerobic sludge digestion. At mixed liquor temperatures above 40 °C, this situation may be reversed , however, given previously reported results from studies of autoheated thermophilic digestion.

This report was submitted in fulfillment of Cooperative Agreement CR-811776 between Cornell University and the U. S. Environmental Protection Agency. This report covers the period from September 1984 through December 1987. All field and laboratory work was completed as of June 1987.

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SECTION 1

INTRODUCTION

BACKGROUND

As shown in Table 1, land application is one of the more commonly utilized methods for the ultimate disposal of municipal wastewater treatment (sewage) sludges in the United States. This is particularly true for small and medium size municipal wastewater treatment plants. With the completion of the phase-out of ocean disposal as required by the 1977 amendments to the Marine Protection, Research, and Sanctuaries Act of 1972 (PL92-532) and the continually decreasing availability of space in landfills, it can be anticipated that land application will be even more widely utilized for the ultimate disposal of these materials in the future.

TABLE 1. ESTIMATED DISTRIBUTION OF MUNICIPAL SLUDGE IN 1980 BY MANAGEMENT METHOD AND TREATMENT PLANT SIZE (MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY, 1983)

Management method	Small <1 MGD	Medium 1-10 MGD	Large >10 MGD	Percent of total
Landspreading on food chain crops	31	22	10	12
Landspreading on non-food chain crops	8	17	11	12
Distribution and marketing	11	13	19	18
Landfill	31	35	12	15
Thermal processing, e.g., incineration	1	1	32	27
Ocean disposal	1	0	4	4
Other, e.g., long-term lagooning	17	12	12	12
Total	100	100	100	100

The practice of sewage sludge ultimate disposal via land application is, in general, both fundamentally sound and economically attractive given that concentrations of heavy metals and toxic organic compounds are at or below established acceptable levels. Even the land application of these "clean" sludges is not without risk, however, due to the possible presence of pathogenic organisms

and the potential for direct or indirect public contact. As shown in Table 2, a variety of pathogenic organisms can be present in municipal wastewaters and hence the resulting sludges.

TABLE 2.PATHOGENIC ORGANISMS COMMONLY FOUND IN MUNICIPAL WASTEWATERS (MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY, 1983; BROCK, 1979; AND METCALF AND EDDY, INC., 1979)

Group	Organism	Disease
Bacteria	Salmonella typhi	Typhoid fever
	Salmonella paratyphi	Paratyphoid fever
	Salmonella spp	Salmonellosis
	Shigella spp	Bacillary Dysentery
	Enteropathogenic Escherichia coli	Gastroenteritis
	Yersinia enterocolitica	Gastroenteritis
	Campylobacter jejuni	Gastroenteritis
	Vibrio chlolerae	Cholera
	Leptospira	Weil's disease
	Francisella tularensis	Tularemia
	Bacillus anthracis	Anthrax
Viruses	Poliovirus	Poliomyelitis
	Echovirus	Meningitis, etc.
	Coxsackie virus	Meningitis, etc.
	New enterovirus	Meningitis, etc.
	Hepatitis Type A	Infectious Hepatitis
Protozoa	Entamoeba histolytica	Amebic dysentery
	Giardia lamblia	Giardiasis
	Balantidium coli	Diarrhea
Helminths	Ascaris lumbricoides	Ascariasis
	Ancyclostoma duodenale	Anemia
	Necator ameriocanus	Anemia
	Taenia saginata	Taeniasis

In recognition of the potential for disease transmission related to the land application of sewage sludges, the U.S. Environmental Protection Agency (USEPA) was required by Subtitle D of the Resource Conservation and Recovery Act (PL94-580) and by Section 405(d) of the Clean Water Act of 1977 (PL95-217) to establish criteria for the control of infectious diseases in the land application of sewage sludges and septic tank pumpings. Such criteria were promulgated by the USEPA in 1979 as part of 40 CFR 257, "Criteria for Classification of Solid Waste Disposal Facilities and Practices" (U.S. Code of Federal Regulations, 1979).

The interim final criteria contained in Section 257.3-6 of 40 CFR 257 specify minimum operating parameters for processes used to stabilize sewage sludges and also septage prior to surface application or incorporation of these materials into the soil. Acceptable treatment processes, designated as "Processes to Significantly Reduce Pathogens", are as follows:

- Aerobic Digestion - The process is conducted by agitating sludge with air or oxygen to maintain aerobic conditions at residence times ranging from 60 days at 15°C to 40 days at 20°C, with a volatile solids reduction of at least 38 percent.

- Air Drying - Liquid sludge is allowed to drain and/or dry on under-drained sand beds, or paved or unpaved basins in which the sludge is at a depth of nine inches. A minimum of three months is needed, two of which temperatures average on a daily basis above 0°C.

- Anaerobic Digestion - The process is conducted in the absence of air at residence times ranging from 60 days at 20°C to 15 days at 35 to 55°C, with a volatile solids reduction of at least 38 percent.

- Composting - Using the within vessel, static aerated pile, or windrow composting methods, the solid waste is maintained at minimum operating conditions of 40°C for 5 days. For four hours during this period the temperature exceeds 55°C.

- Lime Stabilization - Sufficient lime is added to produce a pH of 12 after 2 hours of contact.

- Other Methods - Other methods or operating conditions may be acceptable if pathogens and vector attraction of the waste (volatile solids) are reduced to an extent equivalent to the reduction achieved by any of the above methods.

With the exception of anaerobic digestion, aerobic digestion is probably the most widely used process of the designated processes to significantly reduce pathogens in the United States. Both ease of operation and relatively low capital costs have made aerobic digestion of sewage sludges particularly attractive for small municipal wastewater treatment plants such as those that are common in rural areas. Additional advantages include: (a) low supernatent side-stream biochemical oxygen demand (BOD) and ammonia nitrogen (NH_4-N) concentrations, (b) excellent sludge dewatering characteristics, and (c) an essentially odorless, humus-like biologically stable end product that can be disposed of easily (Metcalf and Eddy, Inc., 1979).

However, several disadvantages also are associated with the use of aerobic digestion for sewage sludge stabilization. The principal disadvantages are high energy costs and the fact that process performance is significantly influenced by climate (Municipal Environmental Research Laboratory, 1979). Due to relatively long residence times, normally a minimum of 10 to 15 days, and the use of open tanks, mixed liquor temperatures can vary by as much as 25°C between summer and winter operation in northern climates.

As with all biological waste treatment processes, the performance of the aerobic sludge digestion process is temperature dependent. As temperature decreases, the rate of microbial activity and thus the rate of oxidation of biodegradable organics, which translates into the rate of stabilization, is reduced. For example, an empirical relationship presented by the Municipal Environmental Research Laboratory (1979) suggests that it is necessary to increase the solids residence time (SRT) from 22.5 days at 25°C to 45 days at 10°C to realize a 40 percent reduction in the concentration of volatile solids. At 5°C, a 90 day SRT would be necessary.

Available evidence suggests that temperature not only affects the rate of sludge stabilization but also the rates of inactivation of pathogens and indicator organisms during aerobic digestion. For example, Kuchenrither and Benefield (1983) reported that with aerobic digestion the densities of both the fecal coliform and fecal streptococcus groups of indicator organisms decreased more rapidly with time as temperature increased. At a residence time of 15 days, an increase in temperature from 20°C to 30°C increased the reduction, $\log_{10}$ basis, of fecal coliforms from 0.91 to 1.56. At 40 °C, no fecal coliforms were detectable. For fecal streptococcus, a temperature increase from 20 °C to 30 °C increased $\log_{10}$ reductions from 0.64 to 1.24. At 40°C, the observed fecal streptococci $\log_{10}$ reduction was 1.71. Similar temperature effects for aerobic digestion also have been reported by Farrah et al. (1986). At a residence time of 15 days, an increase in temperature from 6°C to 28°C increased $\log_{10}$ reductions in the density of Escherichia coli from 0.26 to 1.26. For Streptococcus faecalis, $\log_{10}$ reductions increased from 0.05 to 0.82 and an increase from 0.21 to 1.29 was

observed for the pathogen Salmonella typhimurium. Both of these studies were laboratory scale investigations.

OBJECTIVES

With the exception of the previously cited studies by Kuchenrither and Benefield (1983) and Farrah et al. (1986), little information as noted by Pedersen (1981) has been available concerning the effectiveness of aerobic sludge digestion in reducing the densities of either pathogens or indicator organisms at psychrophilic and mesophilic temperatures. Thus, the investigation described in this report was proposed. The objectives of this study were:

- To determine the seasonal variations in sludge stabilization and reductions in the densities of indicator organisms, Salmonella spp, and enteroviruses that occur with conventional aerobic digestion in cold climates, and
- To demonstrate that both sludge stabilization and reductions in the densities of indicator organisms, Salmonella spp, and enteroviruses can be improved by simple modifications that increase process temperature.

This investigation was a cooperative agreement between Cornell University and the Risk Reduction Engineering Laboratory (RREL) of the United States Environmental Protection Agency (USEPA). The research was conducted at the Trumansburg, New York wastewater treatment plant and in the Waste Management Laboratory, Department of Agricultural Engineering, New York State College of Agriculture and Life Sciences, Cornell University.

SECTION 2

SUMMARY AND CONCLUSIONS

The objectives of this investigation were attained. Seasonal variations in the performance of conventional aerobic sludge digestion in cold climates were characterized. Also, it was demonstrated that process performance could be substantially improved by simple modifications to increase mixed liquor temperatures. From the experimental results obtained in this study, it also was possible to delineate mathematical relationships between residence time and mixed liquor temperature and reductions in the densities of the total coliform, fecal conform, and fecal streptococcus groups of indicator organisms and the enterovirus group of viruses. In addition, it was possible to describe mathematical relationships between residence time and mixed liquor temperature and reductions in total volatile solids and chemical oxygen demand concentrations using results obtained in this study in combination with results reported by other investigators.

In order to achieve the objectives of this investigation, two 32 m^3 aerobic digesters were constructed and operated continuously over a period of 20 months. One digester was designed and operated as an uncovered conventional digester with coarse bubble diffused air aeration. After 17 months of operation, an insulated cover was added to this digester for an additional three months of operation to determine the effect of this simple modification on mixed liquor temperature. Although this modification was not part of the original project plan, it appeared to be a logical step to obtain additional relevant data. The second digester was designed to minimize heat losses and thus, facilitate autoheating. To minimize heat losses, a closed tank with an insulated top was used in combination with a high efficiency mechanical aeration unit. The tap water oxygen transfer efficiency of this aeration unit was determined to be 24 percent, as compared to six percent for coarse bubble diffused air aeration systems.

From 17 months of continuous steady-state conventional digester operation at a constant resistance time of 20 days, it was determined that there was a strong linear relationship between mean monthly mixed liquor and ambient air temperatures. For mean monthly ambient air temperatures of 5°C and 20°C, corresponding mean monthly mixed liquor temperatures were 8°C and 26°C. After the addition of the insulated cover to the conventional digester, mixed liquor temperatures increased substantially. In February 1987, the addition of this insulated cover increased mean monthly mixed liquor temperature from a predicted value of 5°C to the observed value of 23°C. In March 1987, the increase was from a predicted value of 12°C to an observed value of 24°C.

For the autoheated digester, differentials between monthly mean mixed liquor and ambient air temperatures during five periods of steady-state operation varied with ambient air temperature and residence time. This digester was operated at residence times of 10, 15 , and 20 days. Temperature differentials ranged from 24°C to 35°C. The highest mean monthly mixed liquor temperature attained was 40°C at a residence time of 15 days. This is noteworthy as the raw sludge used in this study was relatively dilute. Influent sludge total solids concentrations generally were in the range of one to two percent.

As previously noted, the two aerobic digesters were operated continuously over a period of 20 months. During this period of time, reductions in the densities of the three groups of indicator organisms and the enterovirus group of viruses were determined during eleven separate periods of steady-state operation. This provided a data base of reductions for mixed liquor temperatures ranging from 8°C to 40°C. When these reductions were first ordered with respect to residence time and then temperature, patterns of increasing reductions, $\log_{10}$ basis, with both residence time and mixed liquor temperature became apparent. From subsequent analyses of these data, it was determined that the temperarure dependence of the rates of reduction in the $\log_{10}$ densities of these four groups of microorganisms can be described as Arrhenius type relationships. Due to the limited avaliability of relevant data, it only was possible to test the validity of the Arrhenius type relationships developed for fecal coliforms and fecal streptococci. The degree of agreement between predicted reaction rate coefficients and reaction rate coefficients calculated from the limited results reported by others was found to be reasonable.

The resulting set of four empirical Arrhenius type relationships indicate that the effect of increasing mixed liquor temperature on rate of reduction varies among these four groups of microorganisms. Enteroviruses are the most sensitive to temperature increases while fecal streptococci are the most resistant. For example, a residence time of only 2 days is necessary at 40°C to realize a two $\log_{10}$ reduction in enteroviruses while a residence time of 25 days at 40°C is required for the same reduction in fecal streptococcus density.

During the eleven periods of steady-state operation, reduction in the four parameters used to characterize sludge stabilization; total solids, total volatile solids, chemical oxygen demand, and organic nitrogen; also were determined. When first-order reaction rate coefficients were ordered with respect to temperature, trends of increasing reaction rates with increases in mixed liquor temperature where detectable but correlations were weak. It was possible, however, to delineate mathematical relationships using the Arrhenius equation between first-order reaction rate coefficients for total volatile solids and chemical oxygen demand and mixed liquor temperature. To do this, results from this study were combined with results from two other studies. The mixed liquor temperature range for this combined data base was from 8°C to 62°C.

The resulting mathematical relationships for total volatile solids and chemical oxygen demand indicate that the rates of reductions increase most rapidly as mixed liquor temperatures increase above 30°C. Yet, it appears possible to achieve a 38 percent reduction in total volatile solids concentration at 10°C with a relatively short residence time of 31 days. When residence times necessary to provide a 38 percent reduction in total volatile solids concentrations are compared to residence times necessary to realize two $\log_{10}$ reductions in indicator organisms and enteroviruses for mixed liquor temperatures up to 40°C, residence time for microbial rather than volatile solids reductions appears to be the critical design parameter. At mixed liquor temperatures above 40°C, this situation may be reversed, however, given the results previously reported by Jewell et al. (1982) and Appleton et al. (1986).

Economically, the use of autoheated aerobic digestion for sewage sludge stabilization appears to be attractive. Although insulated digester covers and high efficiency aeration units represent added capital costs, these costs are, at least partially, offset by lower tankage costs due to reduced residence time and thus, volume requirements. In addition, energy costs can be substantially reduced with the use of high efficiency aeration units. For example, autoheated digester energy requirements were 1.34 kWhr/kg of oxygen transferred as compared to 3.32 kWhr/kg of oxygen transferred for the conventional digester in this study.

From the results of this study, it can be concluded that use of aerobic digestion as a process to significantly reduce pathogens assuming two $\log_{10}$ reductions in the densities of coliform

organisms and a 38 percent reduction in total volatile solids concentration as requirements is technically feasible at ambient temperatures at or below freezing. The long residence times required at low mixed liquor temperatures, which are typical during winter months in northern climates, makes operation at these temperatures impractical, however. Yet, it is possible to use aerobic digestion as a process to significantly reduce pathogens in these climates by reducing heat losses through the use of closed reactors with insulated covers singularly or in combination with high efficiency aeration units. Due to the relative simplicity of these modifications, they are applicable not only to new but also existing facilities.

SECTION 3

RECOMMENDATIONS

Given the lack of an adequate data base necessary to test the validity of the set of four predictive equations proposed to describe the relationships between residence time and temperature and reductions in the densities of the three groups of indicator organisms and enteroviruses during aerobic sludge digestion, it is recommended that additional research be conducted to obtain such data. This research should be conducted with a sewage sludge known to routinely contain significant numbers of pathogens such as Salmonella spp so that reliable relationships between reductions in the densities of indicator organisms and pathogens during aerobic digestion can be delineated. Mixed liquor temperatures in such a study, should, at a minimum, range between 5°C and 40°C and preferably between 5°C and 65°C.

It also is recommended that the development and/or testing of high efficiency aeration devices suitable for the aerobic digestion of sewage sludge be encouraged. As discussed in this report, the performance of the autoheated digester aeration unit used in this study was not satisfactory even though it did permit attainment of the study's objectives. The availability of highly efficient methods of aeration would be beneficial not only for aerobic digestion but also for other suspended growth wastewater treatment processes such as the activated sludge process due to opportunities to reduce energy requirements.

Finally, it is recommended that the mathematical model of the aerobic sludge digestion process developed by Andrews and Kambhu (1973) be reviewed, analyzed, and modified as appropriate and then tested to determine the model's validity. The results of this effort should provide a clearer understanding of the complex relationships among mixed liquor temperature, sludge stabilization, biological heat production, and heat losses during the aerobic digestion of sewage sludges and thus, provide a more rational basis for system design.

SECTION 4

LOCATION AND INVESTIGATIVE FACILITIES

LOCATION

The research described in this report was conducted at the municipal wastewater treatment plant located in the Village of Trumansburg, New York. Trumansburg is a small residential community with a sewered population of approximately 2000 people that is located in the finger lakes region of central New York. The village is situated between Cayuga and Seneca Lakes, and is approximately eleven miles northwest of the city of Ithaca which is the location of Cornell University.

The climate of this area made Trumansburg a very appropriate site for this study. This climate is classified as humid continental with cool summers using a modified form of Koppen's classification of world climates (Trewartha, 1954). Average monthly air temperatures range from a low of -5.6°C in January and February to a high of 20°C in July (Figure 1). During the period from mid-December through mid-March, daily minimum temperatures below -12°C are not uncommon and temperatures as low as -23°C to -29°C can occur.

In addition to community characteristics and climate, a number of other factors also contributed to the selection of Trumansburg as the site of this study. They included:

- the interest of the mayor and the village board and their willingness to participate as cooperators,
- the interest of the treatment plant operator, Mr. Gary Gleason of Gleason Environmental Processes, and his staff and their willingness to provide assistance as needed,
- the familiarity of the Cornell personnel involved in this study with the operation of the Trumansburg wastewater treatment plant as the result of previous studies, and
- the close proximity, about 14 miles, of the Village of Trumansburg to the Cornell campus which permitted continual attention.

WASTEWATER TREATMENT PLANT DETAILS

The Trumansburg wastewater treatment plant was built in conjunction with the installation of the village's sanitary sewer system in 1964 and was placed in operation in November of that year. This treatment plant was designed for an average flow of 946 m^3/day and a maximum flow of 2366 m^3/day (Lozier Engineers, Inc., 1963). Design values for five day biochemical oxygen demand (BOD_5) and total suspended solids (TSS) were 227 kg/day and 193 kg/day, respectively. As designed and constructed, the treatment plant consisted of the following components: a comminutor with a

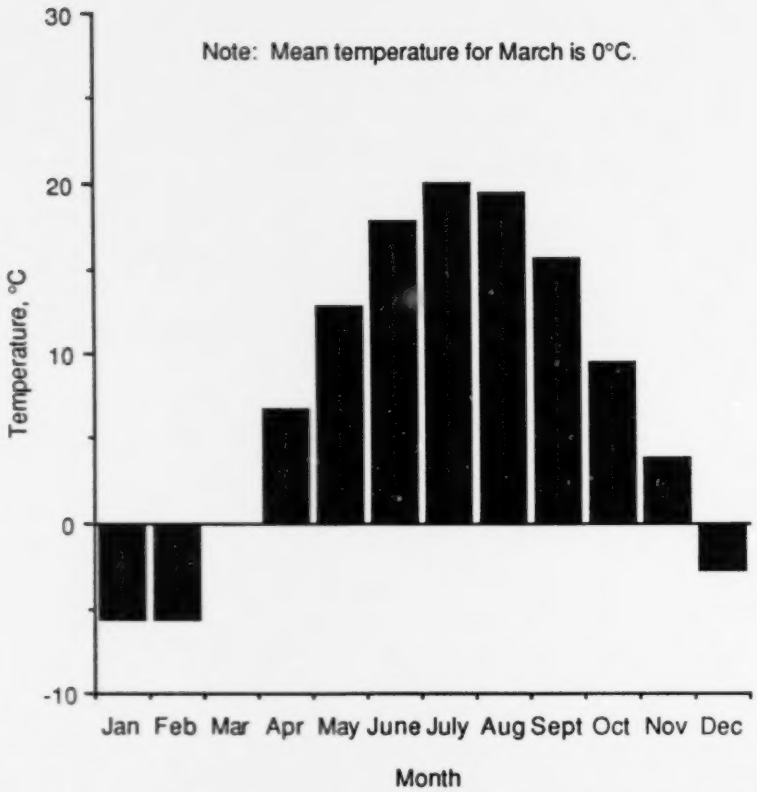

Figure 1. Mean monthly air temperatures for Ithaca, NY, 1958 - 1978 base (Northeast Regional Climate Center, 1986).

manually cleaned bypass bar screen, a mechanically cleaned grit chamber, two parallel aeration basins, two parallel secondary clarifiers, a chlorine contact chamber, a sludge holding tank, and an open sludge drying bed. A plan view of the treatment plant is presented in Figure 2 and the design specifications are summarized in Table 3.

TABLE 3. DESIGN SPECIFICATIONS FOR THE TRUMANSBURG, NY WASTEWATER TREATMENT PLANT (LOZIER ENGINEERS INC., 1963)

Comminutor capacity	-	3785 m^3/day (max.)
Grit chamber capacity	-	3785 m^3/day (max.)
Aeration basins		
Two open basins	-	16.5 m x 7.5 m x 4.0 m, each
Total volume	-	974 m^3
Hydraulic retention time	-	24 hr.
Air supply		
Three centrifugal blowers	-	637 m^3/hr, each
Design air requirements	-	131 m^3 air/kg BOD_5
Diffuser type	-	Coarse bubble
Secondary clarifiers		
Two basins	-	16.5 m x 2.4 m x 2.4 m, each
Total surface area	-	79 m^2
Surface overflow rate	-	12 m^3/m^2-day
Hydraulic retention time	-	4.8 hr.
Sludge collection	-	Chain and flight
Sludge handling facilities		
Sludge holding tank	-	76 m^3
Sludge drying bed	-	116 m^2

The Trumansburg wastewater treatment plant was designed to employ the extended aeration version of the activated sludge process to provide secondary treatment for the village's wastewater. In keeping with the generally accepted approach in the early 1960's for the design of wastewater treatment plants employing extended aeration, primary clarification was omitted and only minimal sludge handling facilities were provided.

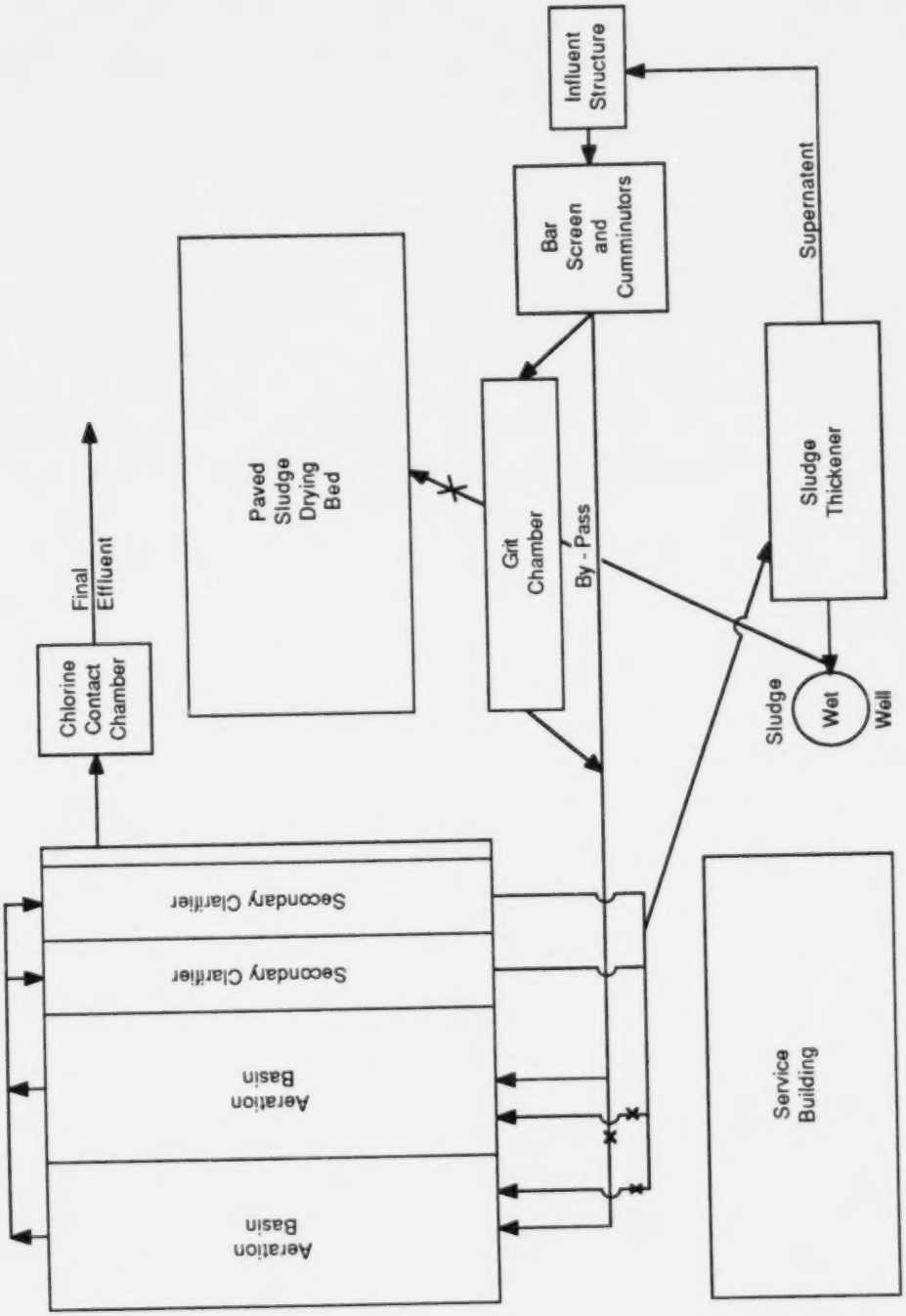

Figure 2. Plan view of the Trumansburg, N.Y. watewater treatment plant.

Within the first year of operation, it became apparent that extended aeration could not provide an acceptable degree of treatment for the village's wastewater. This was due to highly variable and frequently excessive discharges of solids to the effluent receiving stream, Trumansburg Creek. To address this problem, the extended aeration process was replaced with the currently used treatment process, conventional activated sludge. In order to provide the necessary facilities for sludge handling and stabilization, the sludge holding tank was transformed into a gravity thickener and one of the two aeration basins which became superfluous was converted into a conventional aerobic digester. Following stabilization, Trumansburg sludge is lagooned and ultimately disposed of by spreading on agricultural land by a private contractor. Pertinent details for the Trumansburg wastewater treatment plant as currently operated are summarized in Figure 3 and Table 4. As currently operated, removals of five day biochemical oxygen demand (BOD_5) and total suspended solids consistently exceed 90 percent.

TABLE 4. INFLUENT CHARACTERISTICS AND UNIT PROCESS DETAILS FOR THE TRUMANSBURG,NY WASTEWATER TREATMENT PLANT AS CURRENTLY OPERATED.

Influent characteristics	
BOD_5, kg/day	89 ± 24
TSS, kg/day	100 ± 47
Flow, m^3/day	622 ± 64
Aeration basin	
Volume, m^3	487
Hydraulic residence time, hr	18.8
Secondary clarifier	
Volume, m^3	95
Surface area, m^2	39.6
Hydraulic residence time, hr	3.7
Surface overflow rate, $m^3/m^2 \cdot$ day	15.6
Sludge production	
Volume, m^3/day	10.6
Total solids, kg/day	137 ± 18

INVESTIGATIVE FACILITIES

To provide the facilities necessary to satisfy the objectives of this investigation, two 32 m^3 aerobic digesters were added to the Trumansburg wastewater treatment plant. One digester was

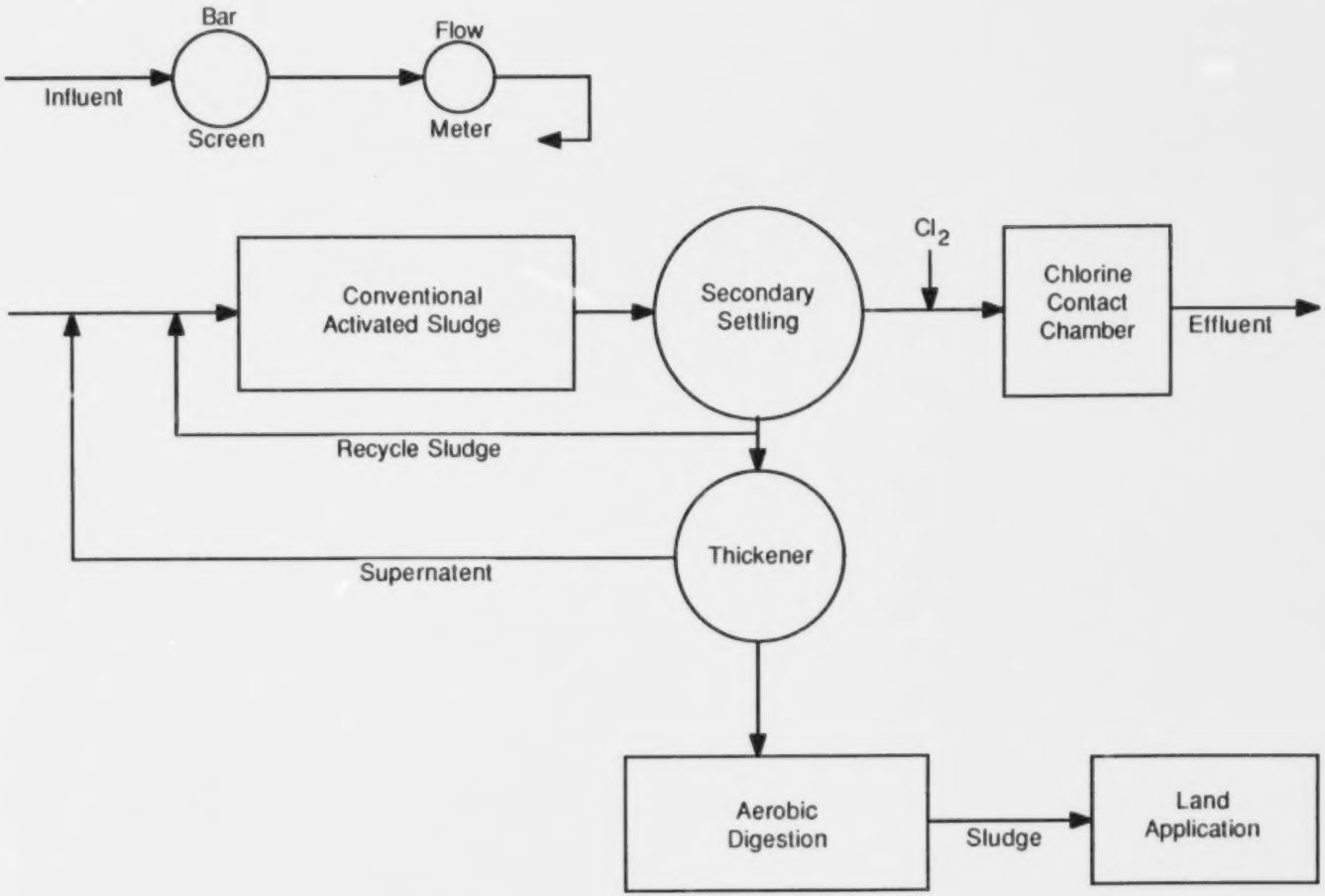

Figure 3. Process flow diagram for the Trumansburg, N.Y. wastewater treatment plant as currently operated.

designed to minimize heat losses and facilitate autoheating while the second was designed to be a conventional aerobic digestion unit. Two vertical 3.66 m diameter by 3.96 m high tanks fabricated from 6.35 mm mild carbon steel plate were used. One tank, the autoheated digester, was a closed tank with a 0.91 m manhole located in the top of the tank to permit access for aerator installation and removal. The second of these two tanks which was used as the conventional digester originally was an open top tank.

Both digesters were insulated with a 7.6 cm coating of 32 kg/m^3 density urethane foam. The foam was covered with an aromatic urethane fast set base coat and a white aliphatic urethane topcoat to prevent loss of insulating value and deterioration due to ultraviolet light. The overall coefficient of heat transfer for the 7.6 cm coating of urethane foam was only 0.24 W/m^2-°C. Following 17 months of operation, an insulated cover was added to the conventional digester to determine the effect of this simple modification on mixed liquor temperatures. Although this modification was not part of the original project plan, it appeared to be a logical step to provide additional relevant data. This cover was fabricated using 5.1 cm thick sheets of styrofoam insulation which has an overall coefficient of heat transfer of 0.57 W/m^2-°C.

In the autoheated digester, a Framco submersible, self-aspirating aeration unit was used. The decision to use this type of aeration unit was based on the following factors:

- effluent gas heat losses would be minimized due to this high oxygen transfer efficiency of this type of aerator,
- partial recycling of the heated effluent gas stream without the difficulties of compressing a gas stream saturated with water vapor in cold weather would be possible,
- the apparent suitability of this type of aeration unit for retrofitting existing aerobic digesters, and
- the apparently satisfactory performance of a Framco aerator in an earlier aerobic sludge digestion study conducted at Cornell University (Jewell et al., 1982).

The design of the Framco aerator is somewhat unique. An open turbine is used to pull mixed liquor through an upper stator plate opening and then discharge it to the periphery of the turbine while drawing an air stream down a draft tube and through the interior of the turbine. Then, the air is discharged to mix with the mixed liquor at the turbine periphery. Finally, the mixed liquor and entrained air bubbles is discharged through channels formed by vanes located between the two stator plates. Photographs of this turbine and the complete aeration unit are presented in Figures 4 and 5, respectively.

Following consultation with the manufacturer of Framco aerators; the Frings Aeration and Mixing Co., Inc., Branford, Connecticut; it was decided to use a 1.5 kw unit, Framco Model 075T. At a depth of three meters, this model has a manufacture's oxygen transfer capacity rating in tap water of 1.54 kg of oxygen per hour under standard conditions at a standard airflow rate of 25 m^3/hr (Fringes Aeration and Mixing Co., Inc.) This translates into an oxygen transfer efficiency of 22 percent as compared to four to eight percent for coarse bubble diffusers commonly used for conventional aerobic sludge digestion (Metcalf and Eddy, Inc., 1979).

Originally, Chicago Pump Discfuser Coarse Bubble Diffusers; FMC Corporation, Chicago, Illinois; were installed in the conventional digester. After 17 months of operation and in conjunction with the addition of an insulated cover to this digester, the coarse bubble diffusers were replaced with Wyss Flex-A-Tube fine bubble diffusers; Parkinson Corporation, Fort Lauderdale, Florida; in an attempt to increase oxygen transfer efficiency which would permit a reduction in air flow rate and thus

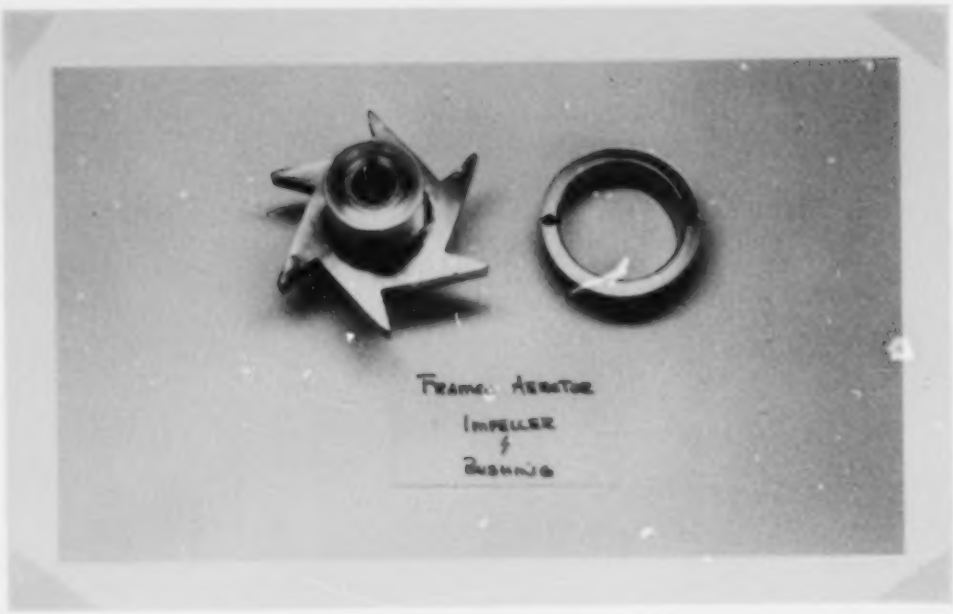

Figure 4. Photograph of the Framco aerator turbine and bushing.

Figure 5. Photograph of the Framco aerator.

heat loss and reduce diffuser fouling problems. The air supply for the conventional digester was provided by 2.2 kw low pressure, rotary positive displacement air pump, Model 12, manufactured by the Condé Milking Machine Co., Inc., Sherril, New York. When operated at the recommended speed of 1200 RPM, this pump has a standard airflow rate of 85 m^3/hr. The Condé air pump was located immediately adjacent to the conventional digester to minimize loss of heat from the compressed air stream. Also, the air pump was enclosed in a small structure to provide weather protection, reduce noise, and minimize heat loss.

In addition to the two tanks used as aerobic digesters, a 9.5 m^3 tank used as an influent mixing tank and a 3.8 m^3 tank used as an effluent surge tank also were added to the Trumansburg wastewater treatment plant. The influent mixing tank was equipped with a 0.75 kw mechanical mixer and a 0.75 kw submersible sludge pump for simultaneous transfer of influent sludge into each of the two digesters.

Both tanks used as aerobic digesters as well as the influent mixing and effluent surge tanks were placed on the treatment plant's unused sludge drying bed as shown in Figure 6. Bases for all four tanks were constructed using used railroad ties. This location provided easy access to raw thickened sludge using an existing pump and piping. Also, this location permitted transfer of the effluents from both digesters to the treatment plant aerobic digester for storage with a minimum of additional piping.

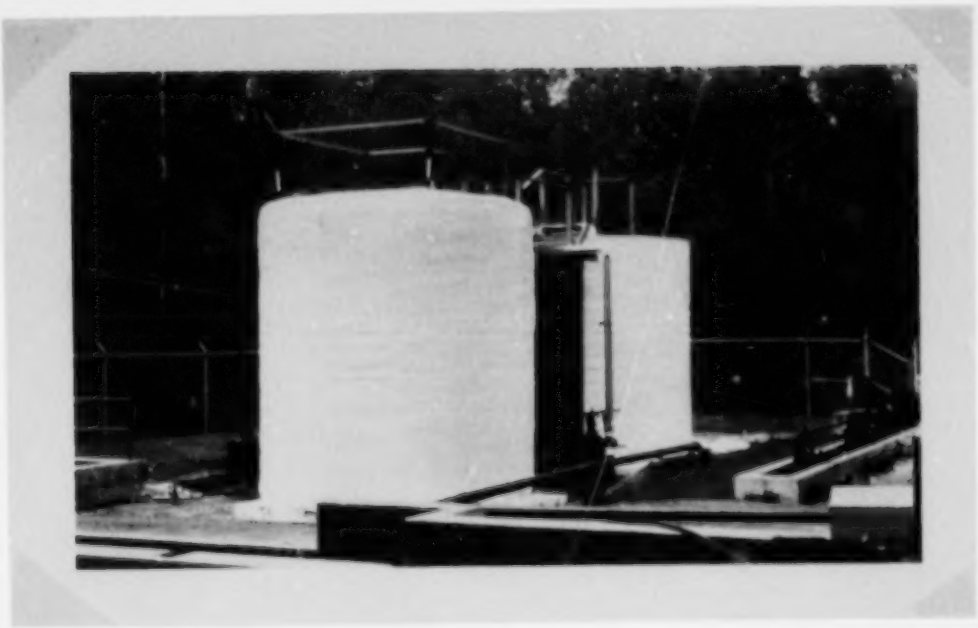

Figure 6 Photograph of the experimental facilities added to the Trumansburg, NY wastewater treatment plant for this study.

SECTION 5

METHODOLOGY

INTRODUCTION

In order to develop the data base necessary to satisfy the objectives of this investigation, the two previously described 32.2 m^3 aerobic digesters located at the Trumansburg wastewater treatment plant were operated continuously from 29 July 1985 through 30 March 1987. During this period, the autoheated digester was operated at residence times of 10,15, and 20 days while the residence time of the conventional digester was held constant at 20 days. The residence time of the conventional digester was held constant at 20 days to determine the seasonal variations in mixed liquor temperature and sludge stabilization and in reductions of enteric microorganisms that occur during conventional aerobic digestion in cold climates. Concurrently, a series of eleven laboratory-scale batch studies also were conducted to provide an estimate of the ultimate biodegradability of the raw, thickened sludge utilized in the field studies. In this section, details of both the field and laboratory studies are presented. Included are descriptions of methods of systems operation and data collection and analyses for physical, chemical, and microbial parameters.

METHODS OF OPERATION AND DATA COLLECTION

Field Studies

Following the completion of oxygen transfer studies on 23 July 1985, both digesters were drained and refilled the next day with sludge that was pumped from the Trumansburg wastewater treatment plant aerobic digester. Both digesters were then operated as batch reactors for the next five days to provide a period for the identification and correction of any possible problems. On 29 July, operation of both digesters as semi-continuous flow draw and fill reactors was initiated and continued without any significant interruptions through 30 March 1987. The frequency of digested sludge withdrawals and raw sludge additions was daily with additions made immediately after withdrawals. The draw and fill mode of operation was selected to eliminate the possibility of effluent characteristics being influenced by short-circuiting of raw sludge additions. Thus, a minimum of 24 hours of treatment always was insured.

Throughout the period 29 July 1985 through 30 March 1987, raw and digested sludge samples were routinely collected and analyzed for concentrations of total solids, total volatile solids, total Kjeldahl nitrogen, ammonia nitrogen, and chemical oxygen demand and pH and temperature. Raw sludge samples were generally collected on Mondays, Wednesdays, and Fridays. These samples were collected during the daily transfer of raw sludge from the mechanically mixed feed tank to the two digesters. Digested sludge samples were generally collected on Tuesdays and Thursdays. These samples were mixed liquor samples taken prior to effluent withdrawal and subsequent raw sludge addition.

During periods of steady-state operation, raw sludge samples collected on Mondays and Wednesdays and digested sludge samples collected on Tuesdays and Thursdays also were analyzed to determine the densities of the total coliform, fecal coliform, and fecal streptococcus groups of indicator organisms and the enterovirus group of viruses. These samples also were analyzed to determine densities of Salmonella spp thru 13 May 1986. At this time, Salmonella enumerations were discontinued as no meaningful data were being obtained. During one period of steady-state data collection, 9 April through 13 May 1986., raw and digested sludge samples also were also analyzed to determine the densities and viability of Ascaris and Toxocara ova. Again, no meaningful data were obtained and these analyses were terminated. During periods of steady-state data collections, a minimum of seven sets of raw and digested sludge samples were collected and analyzed for the microbiological parameters noted above.

All sludge samples were collected using one liter polypropylene bottles which were immediately placed in an insulated container with ice for transport to Cornell. During periods of steady-state data collection, sterilized sample bottles, autoclaved at 121° C for 15 minutes, were used. Determination of the physical and chemical parameters were performed by project personnel at the Cornell University Department of Agricultural Engineering's Game Farm Road Waste Management Laboratory on the day of sample collection. On the days of sample collection for determination of microbial densities, subsamples were transferred aseptically into sterilized 100 mL sample bottles and delivered to the New York State Diagnostic Laboratory, Cornell University College of Veterinary Medicine by project personnel for same day analysis. Subsamples for enterovirus enumerations also were transferred aseptically into sterilized containers and frozen at-20°C in preparation for shipment to the Environmental Monitoring and Support Laboratory (EMSL), USEPA in Cincinnati, Ohio. On the days of digested sludge sample collections, Tuesdays and Thursdays, sets of these frozen raw and digested sludge subsamples were shipped to EMSL in insulated containers containing dry ice with next day delivery. At EMSL, these subsamples were stored at -70°C until analyzed.

Raw sludge and mixed liquor temperatures in both digesters were routinely measured. Raw sludge temperatures were measured and recorded daily during raw sludge additions using a digital thermometer while a continuous record of mixed liquor temperatures was provided by a dual recording thermometer. In addition, a continuous record of ambient temperatures at the field site was obtained using a recording thermograph located in a standard weather instrument shelter. Mean daily mixed liquor and ambient temperatures were calculated by talking the average of the minimum and maximum temperatures recorded in a 24 hour period beginning at 08:00 hours.

Additional data routinely collected and recorded, generally on Mondays, Wednesdays, and Fridays, included mixed liquor dissolved oxygen concentrations and airflow rates. Mixed liquor dissolved oxygen concentrations were measured approximately 24 hours after the previous raw sludge addition using a Clark-type polargraphic oxygen probe with a temperature compensation. In-line rotameters were used to measure airflows to both digesters. Air temperature and pressure also was measured and recorded to permit calculation of airflows under standard conditions. Thus, constant aeration rates were insured.

Batch Studies

As noted, a series of eleven laboratory-scale batch studies also were conducted as part of this investigation. The objective of these studies was to provide an estimate of the biodegradable and refractory fractions of the raw, thickened sludge utilized in the field studies. With such information, it was possible to more precisely define raw sludge characteristics and also to provide a more accurate assessment of the degrees of stabilization realized in the field studies.

In each of these batch studies, three liters of raw, thickened sludge from the Trumansburg

wastewater treatment plant was placed in a four liter glass serum bottle and aerated continuously for 60 days. As shown in Figure 7, humidified, compressed air was supplied via a fritted glass gas dispersion tube at a rate necessary to maintain measurable mixed liquor dissolved oxygen concentrations (>0.5 mg/l) at all times. The mixing action of the compressed air was supplemented using a magnetic stirrer and a teflon coated stir bar to insure completely mixed conditions. Distilled water was added daily to compensate for evaporation. All of these studies were conducted at ambient laboratory temperatures of 20±2°C.

In each study, mixed liquor samples were analyzed on days 0,10,20,30,40,50, and 60 to determine concentrations of total solids, total volatile solids, chemical oxygen demand, total Kjeldahl nitrogen, and ammonia nitrogen. Using these data, the biodegradable and refractory fractions of total solids, total volatile solids, chemical oxygen demand, and organic nitrogen were estimated by plotting the ratio of the concentration of each parameter on day t (S_t) to the initial concentration (S_o) versus the reciprocal of the product of the initial concentration and the elapsed time (t). Then, linear regression was used to determine the mathematical relationship between the two variables. This technique (Jewell et al., 1982) which is illustrated in Figure 8 is based on the assumption that as time approaches infinity the biodegradable fraction of the parameter of interest approaches zero. Thus, the y-axis intercept of the regression line represents the refractory fraction for that parameter.

ANALYTICAL PROCEDURES

The densities of the total coliform, fecal coliform, and fecal streptococcus groups of indicator organisms in both raw and digested sludge samples from the field studies were determined using the methods used by Farrah et al. (1986). Sample preparation, dispersion of sludge flocs to release bacteria was as described by Gaylord and Richards (1970). A modification (Venosa et al., 1979) of the Kenner and Clark procedure (Kenner and Clark, 1974) was used for the detection and enumerations of Salmonella spp. For primary enrichment, three tubes with 10 mL of double-strength nutrient broth, dulcitol selenite enrichment (DSE) broth, were inoculated with 10 mL of sludge, three tubes containing 10 mL of single strength broth were inoculated with one mL of sludge, and a third set of tubes with 10 mL of single-strength broth received 0.1 mL of sludge. These enumerations were conducted under the direction of Dr. Sang J. Shin, Director of Bacteriology at the New York State Diagnostic Laboratory.

As previously noted, enterovirus enumerations were performed by the Environmental Monitoring and Support Laboratory, USEPA. The method used for recovering viruses from the sludges and the BGM cell technique used was as described by Berg et al. (1984). Enumerations of the enteric parasites, Ascaris and Toxocara, also were performed at the New York State Diagnostic Laboratory under the direction of Dr. Richard H. Jacobson. The methods used were those of Reimers et al. (1982).

The analytical methods used to determine the physical and chemical characteristics of raw and digested sludge samples from the field studies are summarized in Table 5. These analytical techniques also were used in the batch studies.

A quality assurance plan was prepared for this investigation in April 1985 and was approved by the EPA project officer and the EPA quality assurance officer. This plan identified sampling and analytical procedures, quality control checks, and procedures to assess data precision and accuracy. As part of this plan, analytical results routinely were reviewed to insure that the quality assurance objectives for precision and accuracy, representativeness, completeness, and comparability were achieved. No problems of substance ever were encountered. In addition to internal quality control checks, a set of Water Pollution Laboratory Performance Evaluation Study (No. 15) samples were

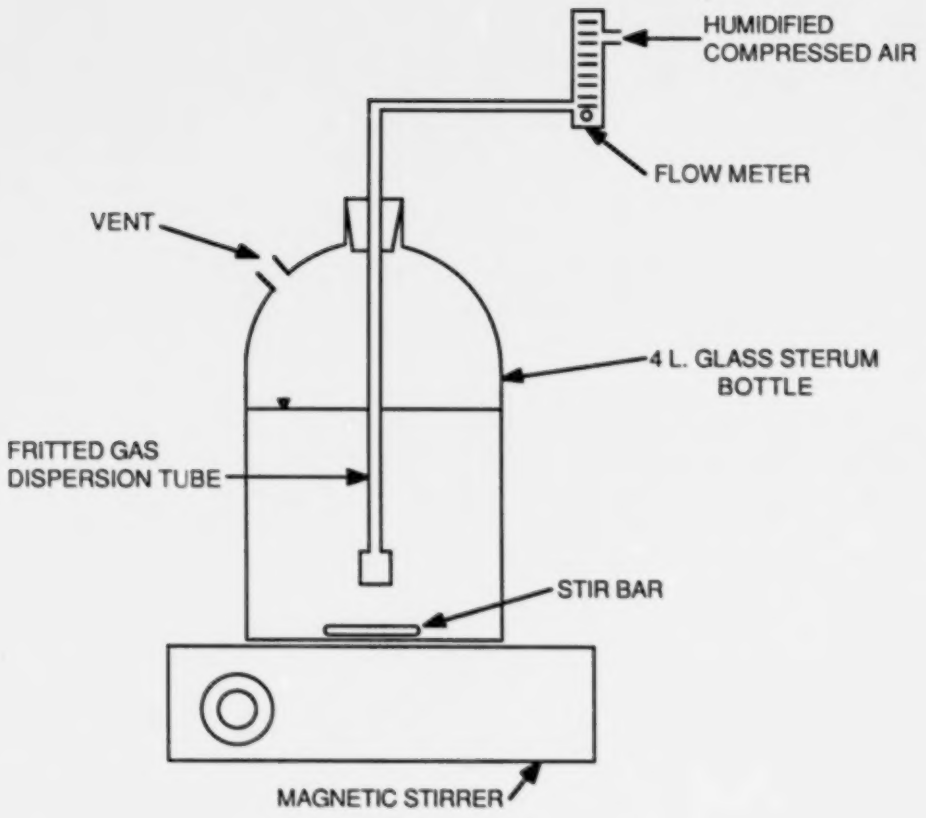

Figure 7. Schematic of reactors and ancillary equipment used for laboratory-scale batch studies.

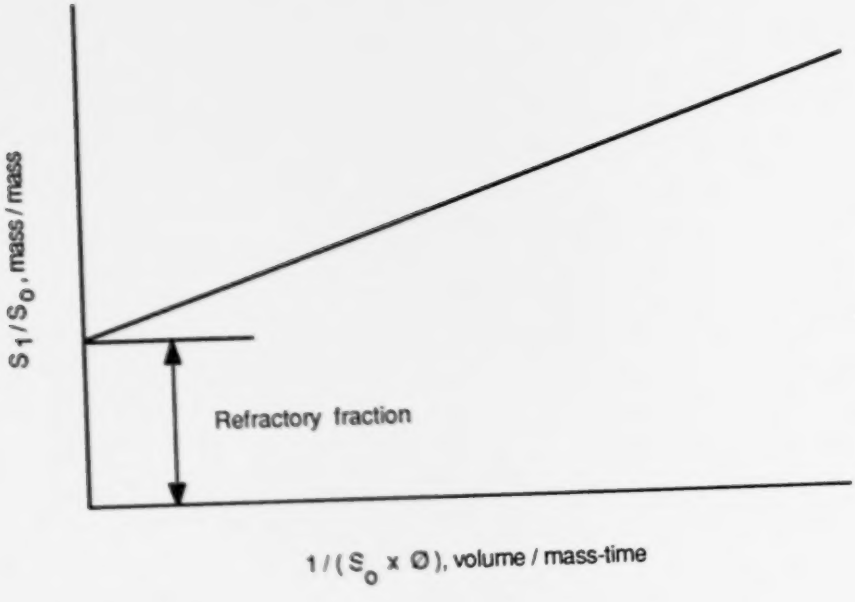

Figure 8. Graphical determination of biodegradable and refractory fractions by reciprocal plot.

analyzed. The results of these analyses compared very favorably with the true values. Also, a quality assurance audit was conducted by PEI Associates, Inc. and resulted in a favorable audit report.

TABLE 5. ANALYTICAL METHODS USED FOR QUANTIFICATION OF THE PHYSICAL AND CHEMICAL CHARACTERISTICS OF INFLUENT AND EFFLUENT SLUDGE SAMPLES.

Parameter	Method
Total residue (Total solids)	Total solids dried at 103-105°C (Standard Methods* 209A)
Total volatile residue (Total Volatile solids)	Fixed and volatile solids ignited at 550°C (Standard Methods 209D)
Chemical oxygen demand	Open reflux method (Standard Methods 508A)
Total Kjeldahl nitrogen	Semi-micro-Kjeldahl method (USEPA † 350.2)
Ammonia nitrogen	Colorimetric distillation procedure (USEPA† 350.2)
pH	pH Value (Standard Methods 434)

*Standard Methods for the Examination of Water and Wastewater (1985)
†Kopp and McKee (1979)

SECTION 6

RESULTS AND DISCUSSION

INTRODUCTION

In order to develop the data base necessary to satisfy the objectives of this investigation, the two 32.2 m^3 aerobic digesters added to the Trumansburg, New York wastewater treatment plant were operated continuously from 28 July 1985 through 30 March 1987. During this period of time, the autoheated digester was operated at residence times of 10,15, and 20 days with two separate periods of steady-state operation at the residence times of 10 and 15 days. Operation at a residence time of five days also was attempted but was terminated before steady-state conditions were established. The oxygen transfer capacity of the Framco aerator was found to be inadequate to satisfy the exerted oxygen demand at this residence time. Thus, there were five periods of steady-state operation of the autoheated digester during which data to characterize performance with respect to mixed liquor temperature, reductions in the densities of the three groups of indicator organisms and the enterovirus group of viruses, and sludge stabilization were obtained. The dates of these five periods of autoheated digester steady-state operation are noted in Table 6.

Also noted in Table 6 are the dates of concurrent data collection to characterize the performance of the conventional digester using the same parameters that were used for the autoheated digester. The additional period of data collection for the conventional digester, 28 July through 3 September 1986, without concurrent data collection for the autoheated digester was due to an atypical period of excessive autoheated digester foaming. As a result of this problem, loss of significant amounts of foam and thus mixed liquor occurred on several occasions. Also, mixing was impaired making it impossible to obtain representative mixed liquor samples. The factor or factors responsible for this atypical period of excessive foaming remain unclear. Although there also was more foam than normal in the conventional digester during this period of time, it was possible to continue data collection resulting in the additional period of steady-state operation.

In the following, the results obtained during the steady-state operation of the two digesters are summarized and discussed. The results of tap water oxygen transfer studies conducted during July 1985 and the series of laboratory scale batch studies conducted to assess the biodegradability of Trumansburg sludge also are presented and discussed.

OXYGEN TRANSFER STUDIES

At the outset of the experimental phase of this investigation, a series of tap water oxygen transfer studies were conducted. The objectives of these studies were to:

- determine the oxygen transfer capacity of each of the two aeration systems being used in this study, and

- provide a basis for comparing the efficiency of these two types of aeration systems.

TABLE 6. PERIODS OF STEADY-STATE OPERATION USED TO CHARACTERIZE AUTOHEATED AND CONVENTIONAL DIGESTER PERFORMANCE

Dates	Residence Time, Days	
	Autoheated	Conventional
6 Nov - 5 Dec 85	20	20
6 Jan - 30 Jan 86	10	20
9 Apr - 13 May 86	15	20
28 July - 3 Sept 86	–	20
15 Sept - 9 Oct 86	10	20
2 Feb - 26 Mar 87	15	20

For the conventional digester with a coarse bubble diffused air aeration system, oxygen transfer rates at airflows of 34 m^3/hr and 51 m^3/hr were determined. For the autoheated digester with the Framco submersible aerator, oxygen transfer was determined at the naturally aspirated airflow rate of 22 m^3/hr. The results of these oxygen transfer rate determinations are summarized in Table 7.

TABLE 7. RESULTS OF TAP WATER OXYGEN TRANSFER STUDIES COMPARING COARSE BUBBLE DIFFUSED AIR AERATION WITH A FRAMCO SUBMERSIBLE AERATION UNIT.

Method of aeration	Airflow, m^3/hr*	$K_La_{20°C}$, † min^{-1}	Oxygen transfer, kg/hr	Oxygen transfer efficiency, %
Coarse bubble diffused air	34	0.032±0.001	0.56	5.9
	51	0.048±0.002	0.84	5.9
Framco submersible aerator	22	0.085±0.002	1.49	24.2

*at 20°C, 760 mm Hg

†mean ± standard deviation, n=3

As shown in this table, the oxygen transfer efficiency of the Framco aerator was exceptionally high and greatly exceeded that of the coarse bubble diffused air aeration system The observed

oxygen transfer efficiencies for both the Framco aerator and the coarse bubble diffused air aeration system are typical of such systems. (Fringes Aeration and Mixing Co., Inc., and Metcalf and Eddy, Inc., 1979).

TEMPERATURE

As shown in Figure 9, mean monthly air temperatures throughout the course of this study varied little from long-term, 1958-1978, means. Overall, there was only a +0.2°C deviation from the normal mean temperature for the time period noted in Figure 9. The lowest daily mean temperature recorded, -19°C, occurred on 25 January 1987 while maximum daily mean temperatures of 26°C occurred on 15 August 1985 and 26 July 1986.

With respect to mixed liquor temperatures, both digesters performed as anticipated. In the conventional digester, daily mean mixed liquor temperatures ranged from 5°C with some surface ice formation during extended periods of cold weather to 28°C during summer months. Monthly means of mixed liquor temperatures ranged from 8°C to 26°C and varied seasonally with ambient air and influent sludge temperatures (Figure 10). Results of regression and correlation analyses (Snedecor and Cochran, 1980) indicate that there was a very strong linear relationship between monthly means of ambient air and conventional digester mixed liquor temperatures as illustrated by Figure 11. The relationships between monthly mean ambient air and influent sludge temperatures and between monthly mean influent sludge and conventional digester mixed liquor temperatures also were found to be linear with correlation coefficients 0.93 and 0.89, respectively (Figures 12 and 13).

The immediate effect of modifying the conventional digester by adding an insulated cover in January 1987 is shown in Figure 14. It is particularly noteworthy that the 10°C increase in mixed liquor temperature that followed the completion of the insulated cover occurred during one of the more severe periods of cold weather encountered during this study. The mean ambient air temperature for the period 16 January through 31 January 1987 was -8.6°C. The effect of the insulated cover on conventional digester mixed liquor temperatures under steady-state conditions is illustrated by the comparisons presented in Figure 15.

Mixed liquor temperatures for each of the five periods of autoheated digester steady-state operation (Table 6) are summarized and compared with ambient air and influent sludge temperatures in Table 8. Autoheated and conventional digester mixed liquor temperatures during periods of concurrent steady-state operation are compared in Table 9. As shown in these tables, the design of the autoheated digester provided substantially higher mixed liquor temperatures as compared to both ambient air and influent sludge temperatures and also to mixed liquor temperatures in the open conventional digester.

RAW SLUDGE CHARACTERISTICS

Microbial Characteristics

During the 18 month period beginning in November 1985, the densities of the total coliform, fecal coliform, and fecal streptococcus groups of indicator organisms and the enterovirus group of viruses in the Trumansburg wastewater treatment plant raw thickened sludge were determined during six separate sampling periods (Table 6). The duration of these sampling periods ranged from 24 to 50 days with between seven and nine samples per sampling period. The results of these enumerations expressed on a colony-forming unit or a plaque-forming unit as appropriate per 100 mL of sample and per gram of total solids basis are presented in Tables A-1 and A-2, respectively and are summarized in

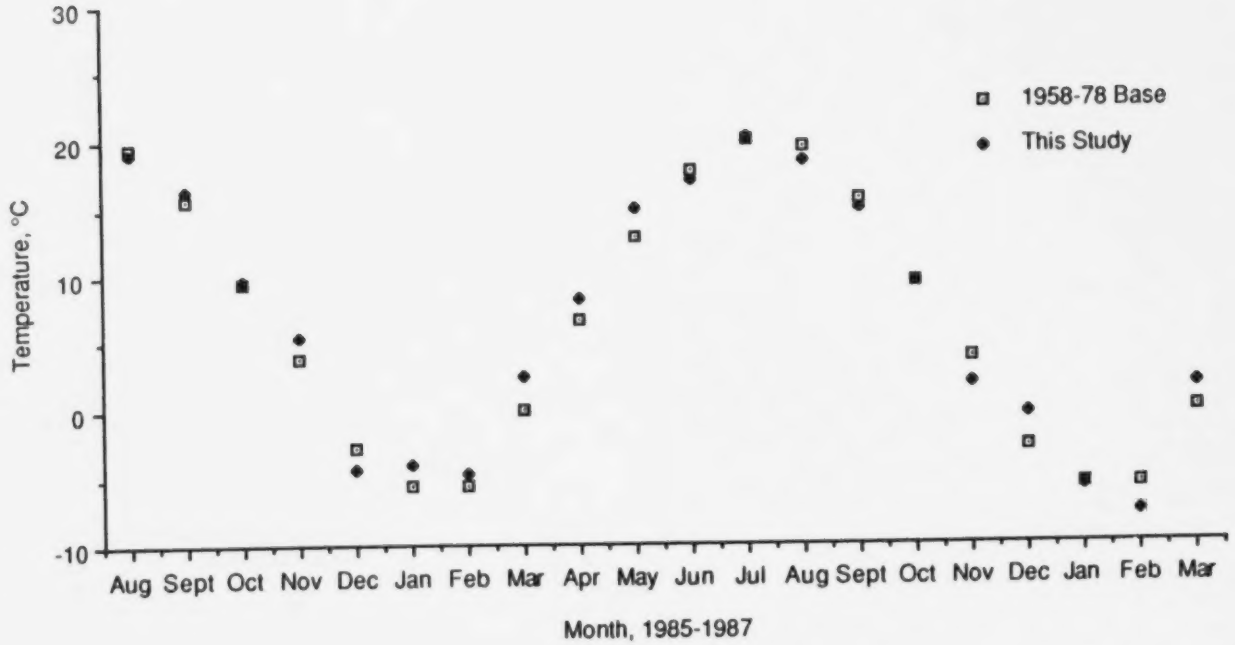

Figure 9. Comparison of mean monthly air temperatures.

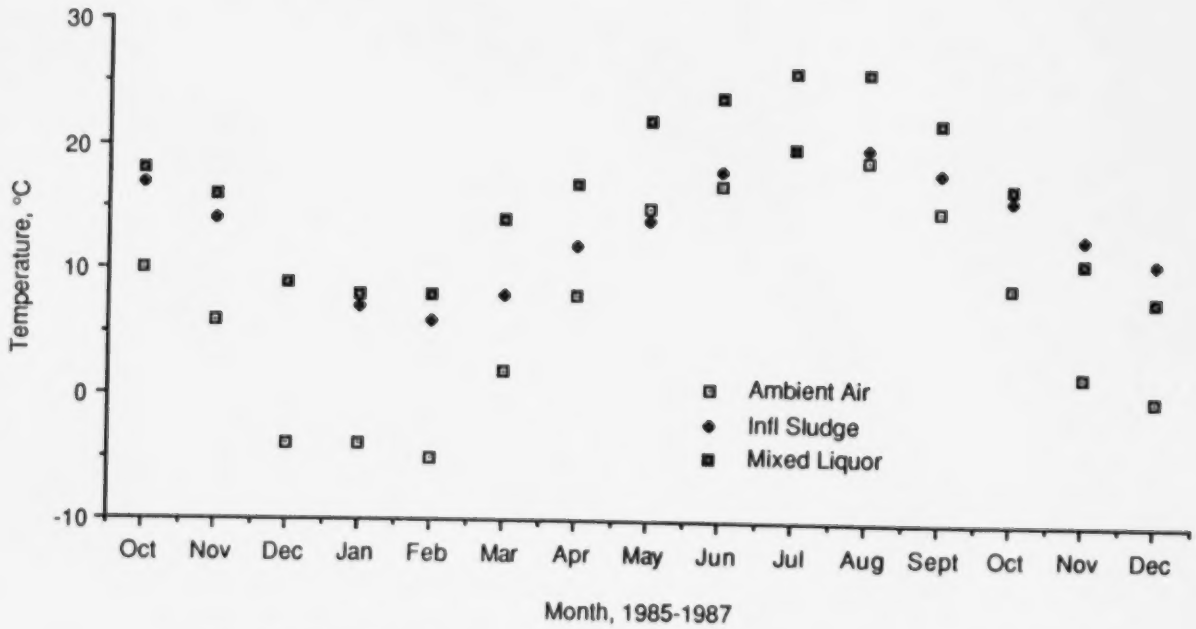

Figure 10. Seasonal variations in ambient air, influent sludge, and conventional digester mixed liquor temperatures for October 1985 through December 1986.

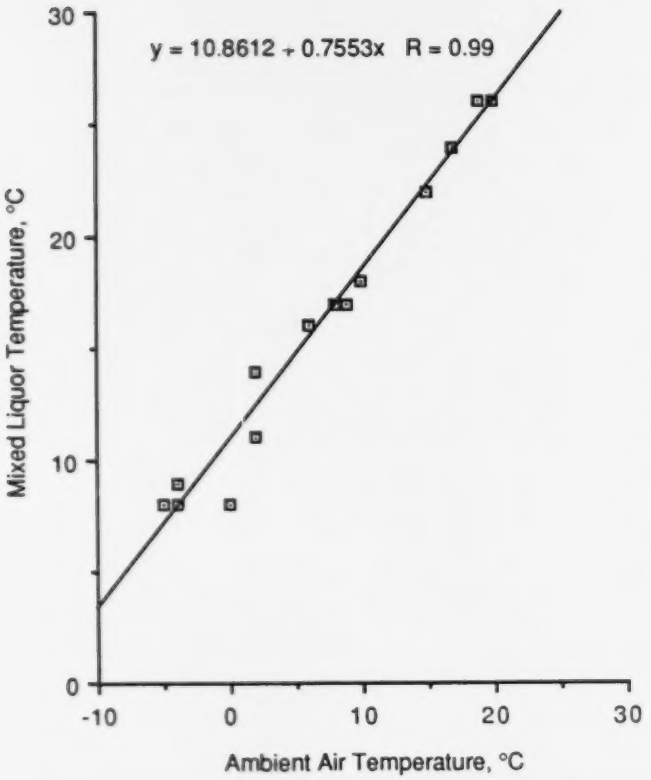

Figure 11. Conventional digester mixed liquor temperature as a function of ambient air temperature.

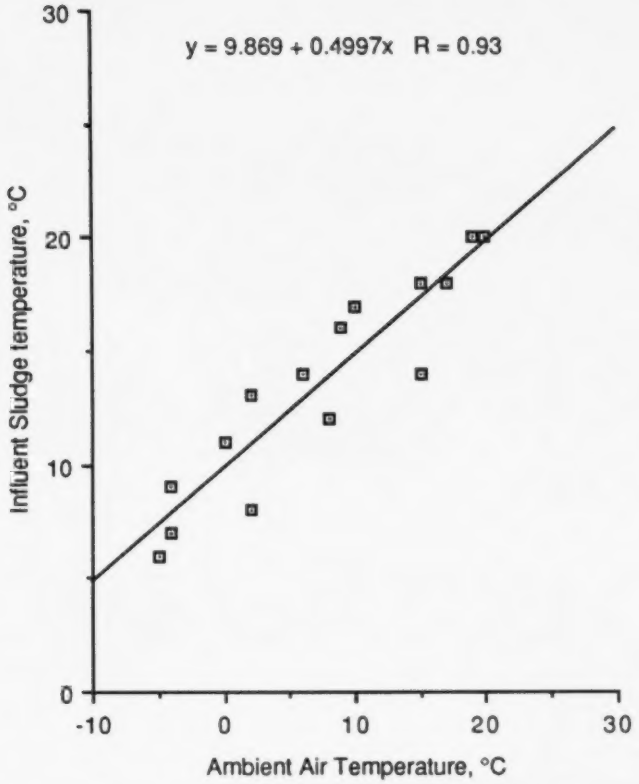

Figure 12. Influent sludge temperature as a function of ambient air temperature.

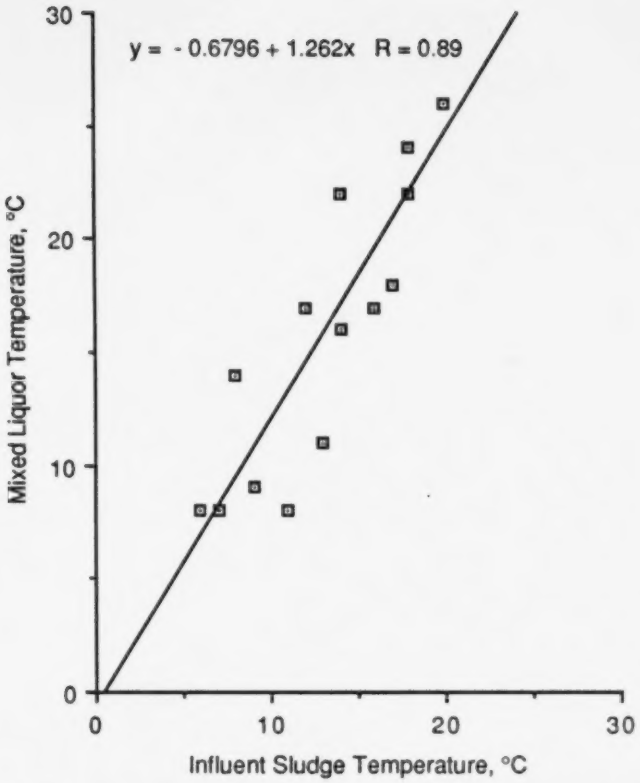

Figure 13. Conventional digester mixed liquor temperature as a function of influent sludge temperature.

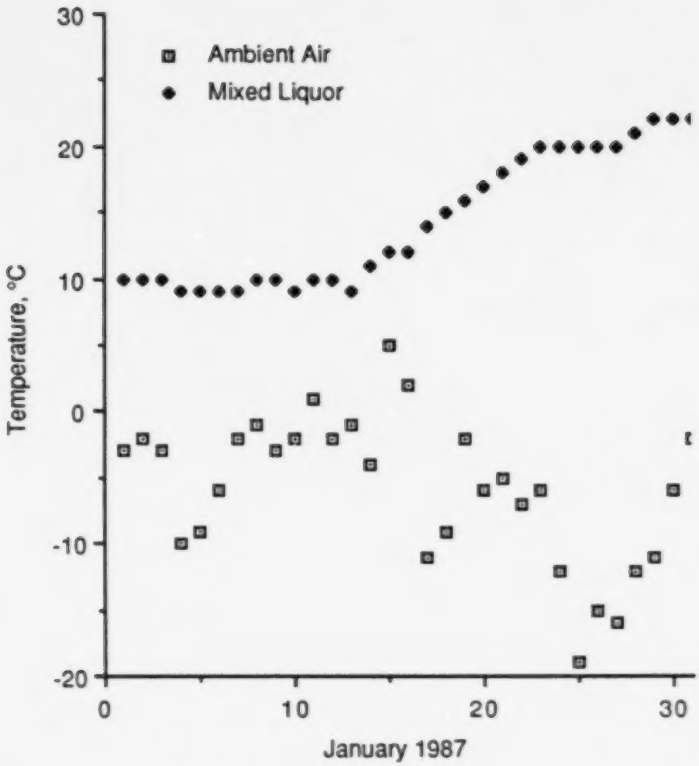

Figure 14. The effect of adding an insulated cover to the conventional digester on 12 January 1987.

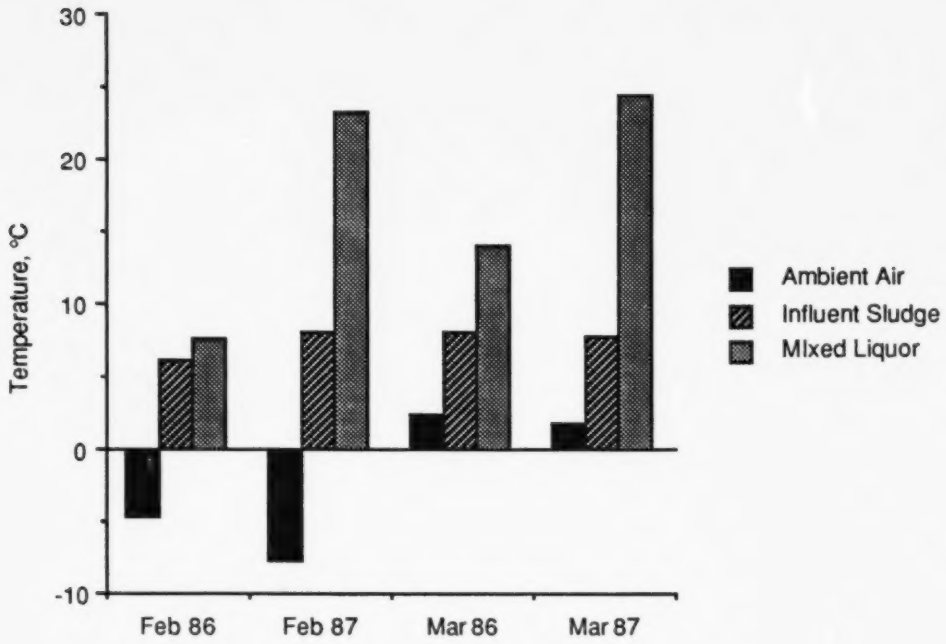

Figure 15. Comparisons of conventional digester steady-state mixed liquor temperatures without (1986) and with (1987) an insulated cover.

TABLE 8. SUMMARY OF AMBIENT AIR, INFLUENT SLUDGE, AND AUTOHEATED DIGESTER MIXED LIQUOR TEMPERATURES DURING PERIODS OF STEADY-STATE OPERATION.

Dates	Residence time, days	Temperature, °C*		
		Ambient air	Influent sludge	Autoheated digester mixed liquor
6 Nov - 65 Dec 85	20	3.9 ± 4.6	12.8 ± 1.4	38.2 ± 0.9
6 Jan - 30 Jan 86	10	-4.3 ± 7.0	6.8 ± 0.7	31.0 ± 1.2
9 Apr - 13 May 86	15	9.3 ± 5.8	12.2 ± 1.4	39.8 ± 2.4
15 Sept - 9 Oct 86	10	13.9 ± 4.4	17.4 ± 1.0	37.5 ± 1.3
2 Feb - 26 Mar 87	15	-3.8 ± 7.2	7.7 ± 1.0	29.0 ± 1.5

*Mean ± Standard Deviation

Table 10.

TABLE 9. COMPARISON OF AUTOHEATED AND CONVENTIONAL DIGESTER MIXED LIQUOR TEMPERATURES DURING CONCURRENT PERIODS OF STEADY-STATE OPERATION.

Dates	Mixed Liquor Temperature, °C*	
	Autoheated	Conventional
6 Nov - 5 Dec 85	38.2 ± 0.9	14.6 ± 2.1
6 Jan - 30 Jan 86	31.0 ± 1.2	8.0 ± 1.6
9 Apr - 13 May 86	39.8 ± 2.4	17.5 ± 2.3
15 Sept - 4 Oct 86	37.5 ± 1.3	21.7 ± 2.0
2 Feb - 26 Mar 87	29.0 ± 1.5	23.7† ± 1.1

*Mean ± standard deviation
†Conventional digester with insulated cover.

As shown in Table 11, there were substantial variations in the densities of each of the three groups of indicator organisms and also the enterovirus group of viruses within each sampling period. Results of one-way analyses of variance (Snedecor and Cochran, 1980) indicate that there also were statistically significant differences ($P<0.01$) among the geometric mean densities of all four groups of microorganisms between sampling periods. The results of comparisons of each mean value with every other mean value within each group of microorganisms using Fisher's protected least significant difference test (Steel and Torrie, 1980) also are summarized in Table 11. It appears that these differences among sampling periods were random as there is no apparent seasonal pattern and no statistically significant correlation ($P<0.05$) with sludge temperature.

As previously discussed, raw sludge samples also were routinely analyzed to estimate the densities of Salmonella spp. during the first three periods of concurrent autoheated and conventional digester steady-state operation (Table 6). During the third period of steady-state operation, raw sludge samples also were routinely analyzed to determine Ascaris and Toxocara ova densities and the viability of the recovered ova. Unfortunately, the results of these enumerations provided no meaningful data. Detectable numbers of Salmonella spp. were found in only four of the 23 raw sludge samples analyzed. Two of these positive samples had Salmonella spp. densities (MPN) of 190 per 100 mL while the other two positive samples had densities of 29 per 100 mL. In the nine raw sludge samples analyzed for Ascaris and Toxocara ova, no viable ova were recovered. Given these results, further analyses for Salmonella spp. and Ascaris and Toxocara ova were deemed to be futile and the remaining financial resources were re-allocated to other areas of inquiry.

The data base of the densities of indicator organisms and enteroviruses in the Trumansburg wastewater treatment plant raw thickened sludge (Table 11) provided the opportunity to examine the nature of the relationships among these four groups of microorganisms in municipal wastewater treatment sludges. Of specific interest was the question of dependence. As the geometric means of the densities of each group of microorganisms for the six sampling periods, $n = 6$, were found to be

TABLE 10. INFLUENT SLUDGE DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES IN TRUMANSBURG, NY RAW THICKENED SLUDGE.

		11/6 - 12/4/85	1/6 - 1/29/86	4/9 - 5/12/86
Total coliforms*	$\bar{X}$¥	6.66	5.79	6.14
	SD#	0.66	0.81	0.24
	Range	5.89 - 8.04	5.72 - 6.64	5.76 - 6.61
	n	7	8	9
Fecal coliforms*	$\bar{X}$	5.60	5.00	4.58
	SD	0.44	0.40	0.18
	Range	5.04 - 6.26	4.43 - 5.75	4.23 - 4.85
	n	7	8	9
Fecal streptococci*	$\bar{X}$	4.70	4.32	4.07
	SD	0.19	0.45	0.24
	Range	4.40 - 4.89	3.32 - 4.93	3.53 - 4.40
	n	7	8	9
Enteroviruses†	$\bar{X}$	3.11	3.01	2.18
	SD	0.11	0.14	0.17
	Range	3.01 - 3.36	2.78 - 3.27	1.89 - 2.37
	n	7	8	9

TABLE 10. Continued.

		7/28 - 9/2/86	9/15 - 10/8/86	2/2 - 3/23/87
Total coliforms*	$\bar{X}$	5.49	5.28	6.52
	SD	0.29	1.02	0.53
	Range	4.98 - 5.87	3.95 - 6.93	5.32 - 7.00
	n	8	8	8
Fecal coliforms*	$\bar{X}$	3.81	4.61	4.65
	SD	0.40	0.67	0.56
	Range	2.98 - 4.43	4.15 - 6.26	3.52 - 5.28
	n	8	8	8
Fecal streptococci*	$\bar{X}$	3.72	3.91	4.21
	SD	0.34	0.24	0.48
	Range	2.94 - 4.11	3.43 - 4.30	3.45 - 4.79
	n	8	8	8
Enteroviruses†	$\bar{X}$	3.03	2.94	2.27
	SD	0.61	0.16	0.38
	Range	2.98 - 3.42	2.72 - 3.14	1.65 - 2.73
	n	4	5	8

*Colony-forming units per gram of total solids

†Plaque-forming units per gram of total solids

¥Mean of the Log_{10} densities

#Standard deviation of the Log_{10} densities

TABLE 11. STATISTICAL COMPARISON OF THE LOG_{10} MEANS OF TRUMANSBURG, NY RAW THICKENED SLUDGE INDICATOR ORGANISM AND ENTEROVIRUS DENSITIES*.

	11/6 - 12/4/85	1/6 - 1/29/86	4/9 - 5/12/86	7/28 - 9/2/86	9/15 - 10/8/86	7/2 - 3/23/87
Total coliforms	$6.65^{a\dagger}$	6.04^{ab}	6.14^{a}	5.49^{bc}	5.28^{c}	6.52^{a}
Fecal coliforms	5.60^{a}	5.02^{b}	4.58^{b}	3.81^{c}	4.61^{b}	4.65^{b}
Fecal streptococci	4.70^{a}	4.32^{b}	4.07^{bc}	3.72^{c}	3.91^{c}	4.34^{ab}
Enteroviruses	3.11^{ac}	3.01^{ac}	2.17^{b}	3.28^{c}	2.94^{a}	2.27^{b}

*Colony-forming or plaque-forming units per gram of total solids, log_{10} basis

†Geometric means in the same row with a common superscript are not significantly different ($P<0.05$).

normally distributed ($P<0.01$) using the Kolmogorov - Smirnov Test (Rohatgi, 1976), it was possible to use correlation analysis (DeVore, 1982) using the sample correlation coefficient, R, as a point estimate for the population correlation coefficient, ρ, to test for linear dependence among these four groups of microorganisms. Where the sample correlation coefficients were not equal to zero suggesting linear independence, the Student's t distribution with n-2 degrees of freedom (DeVore, 1982) was used to test the null hypothesis $\rho = 0$.

The results of these correlation analyses are summarized in Table 12. As shown in this table, there was a strong and highly significant ($P<0.01$) linear correlation between the densities of fecal coliforms and fecal streptococci. The null hypothesis that $\rho=0$ also was rejected at the $P<0.05$ level of significance for the relationship between total coliforms and fecal streptococci. The correlation coefficients for the relationships between total coliforms and fecal coliforms and between the enterovirus group of viruses and each of the three groups of indicator organisms were not significantly different from zero ($P<0.05$), however, suggesting statistical independence.

TABLE 12. RESULTS OF CORRELATION ANALYSES TO TEST FOR LINEAR DEPENDENCE AMONG THE THREE GROUPS OF INDICATOR ORGANISMS AND ENTEROVIRUSES IN TRUMANSBURG RAW SLUDGE.

Correlation	Correlation Coefficient, R
Total coliforms and fecal coliforms	0.668*
Total coliforms and fecal streptococci	0.880†
Total coliforms and enteroviruses	0.396*
Fecal coliforms and fecal streptococci	0.925¥
Fecal coliforms and enteroviruses	0.003*
Fecal streptococci and enteroviruses	0.103*

*Not significantly different from $\rho=0$ ($P<0.05$)
†Significantly different from $\rho=0$ ($P>0.95$)
¥Significantly different from $\rho=0$ ($P>0.99$)

The absence of strong linear correlations ($P<0.01$) between the densities of total coliforms and fecal coliforms and between total coliforms and fecal streptococci in the raw sludge was unexpected. Variations in the densities of Enterobacter aerogenes which are part of the total coliform group of indicator organisms but generally not of enteric origin (Brock, 1979) were probably responsible for the absence of the expected strong correlations. In contrast, the absence of even moderately strong correlations ($P<0.05$) between enterovirus densities and the densities of each of the three groups of indicator organisms was not unexpected. It would be illogical to expect such correlations as enteroviruses as well as other pathogens are not, unlike fecal coliforms and fecal streptococci, normal inhabitants of the human gastro-intestinal tract, but rather present only in infected individuals. The absence of even moderately strong correlations between enterovirus densities and the densities of each of the three groups of indicator organisms in raw sludges also has been reported by Berg and Berman, (1980). Conversely, the strong correlation between raw sludge densities of fecal coliforms and fecal streptococci was not surprising as both of these groups of indicator organisms include only organisms of enteric origin.

Physical and Chemical Parameters

Throughout the course of the field studies conducted at the Trumansburg wastewater treatment plant, raw thickened sludge concentrations of total solids, total volatile solids, chemical oxygen demand, and total Kjeldahl nitrogen as well as pH were relatively constant. As shown in Figure 16, monthly means of total solids concentrations ranged from 10,200 mg/L to 17,600 mg/L. Total volatile solids, chemical oxygen demand, and total Kjeldahl nitrogen concentrations varied over comparable ranges. Raw sludge composition also was relatively constant as illustrated in Figure 16. The monthly variations in raw sludge concentrations of total solids, etc. (Figure 16) are reflections of daily variations that were somewhat more extreme but generally cyclical in nature. These daily variations were due to changes in treatment plant and thickener performance which typically occurred during periods of high treatment plant influent flows due to infiltration and inflow.

Results of the eleven laboratory-scale batch studies are summarized in Table 13. These results indicate that the biodegradability of Trumansburg sludge was quite variable during the period of the field studies. The most variable parameter was the biodegradable fraction of total solids which ranged from 31 percent to 54 percent. Most likely, this was due to varying amounts of grit as the Trumansburg wastewater treatment plant did not have an operational grit chamber during the course of this study. Although the estimated biodegradable fractions of total volatile solids, chemical oxygen demand, and organic nitrogen were less variable, the observed ranges of values for these parameters were still substantial as noted in Table 13. There were no apparent seasonal trends in the observed estimates of biodegradable fractions. Also, there were no strong correlations among the estimated biodegradable fractions of total volatile solids, chemical oxygen demand, and organic nitrogen. There was, however, a strong correlation, $R=0.95$, between the estimated biodegradable fractions of total solids and total volatile solids as would be expected.

FIELD STUDIES

As noted in Table 6, there were five periods of autoheated digester and six periods of conventional digester steady-state operation during the course of this investigation. In the following, the data collected to characterize the reductions of indicator organisms and enteroviruses and the degree of sludge stabilization are summarized and discussed.

Microbial Reductions

In Tables 14 through 19, geometric means of influent (raw sludge) and effluent densities of the total coliform, fecal coliform, and fecal streptococci groups of indicator organisms and the enterovirus group of viruses are summarized and compared statistically. One-way analyses of variance (Snedecor and Cochran, 1980) followed by Fisher's protected least significance difference test (Steel and Torrie, 1980) was used to perform these comparisons. The geometric mean densities summarized in these tables were calculated from the results of influent and effluent sample enumerations presented on a per 100 mL of sample basis in Appendix A, Tables A-1, A-3, and A-5. Also included in Appendix A are the results of these enumerations presented on a per gram of total solids basis, Tables A-2, A-4, and A-6. In Appendix B, geometric means of influent and effluent densities on a per gram of total solids basis are summarized and compared statistically, Tables B-1 through B-6.

Generally, the geometric means of the effluent densities of each of the three groups of indicator organisms as well as the enterovirus group of viruses were significantly lower ($P<0.05$) than the influent geometric means. The only exceptions occurred during the 6 January - 30 January 1986 (Table 15) and the 15 September - 9 October 1986 (Table 18) periods of steady-state operation.

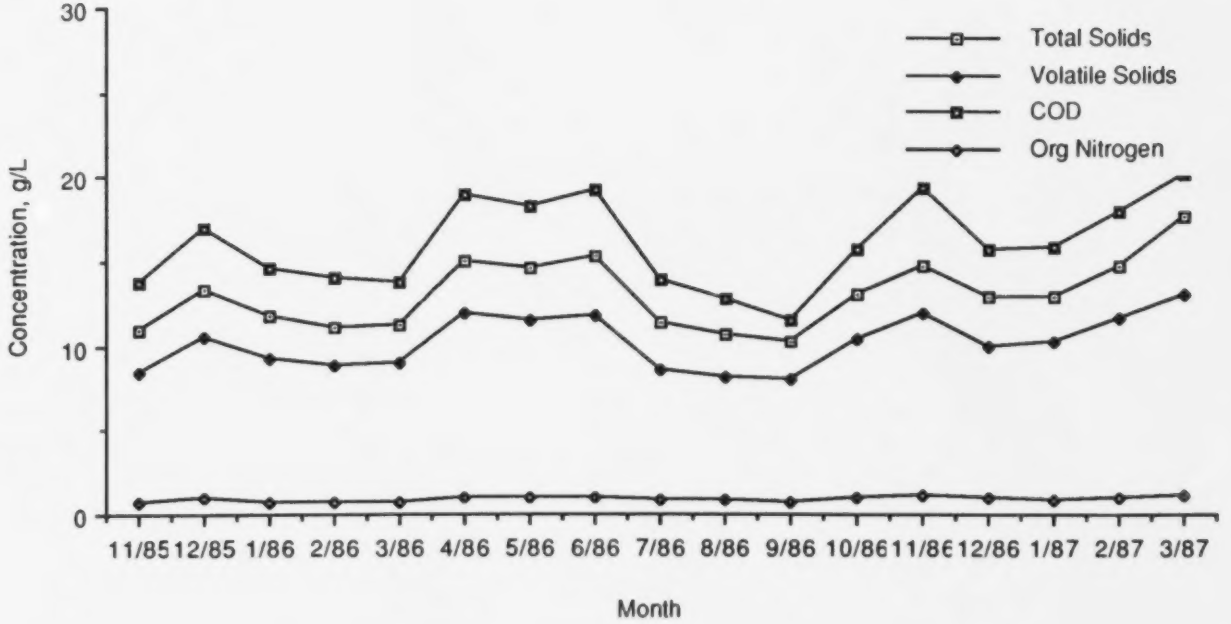

Figure 16. Summary of monthly means of influent sludge characteristics.

During the period of 6 January - 30 January 1986, there was no statistically significant difference between the geometric means of influent and conventional digester effluent fecal streptococcus densities (Table 15.) It appears that this lack of a statistically significant reduction in fecal streptococci density was due to the low conventional digester mixed liquor temperature, 8.0 ± 1.6°C, during this period of steady-state operation.

TABLE 13. SUMMARY OF RESULTS OF BATCH STUDIES CONDUCTED TO ESTIMATE RAW SLUDGE BIODEGRADABILITY.

Study No.	Biodegradable fraction			
	Total Solids	Total Volatile Solids	Chemical Oxygen Demand	Organic Nitrogen
1	0.40	0.49	0.65	0.65
2	0.40	0.55	0.66	0.60
3	0.42	0.51	0.72	0.75
4	0.36	0.49	0.68	0.63
5	0.37	0.47	0.64	0.66
6	0.54	0.62	0.74	0.78
7	0.33	0.45	0.62	0.66
8	0.31	0.43	0.54	0.67
9	0.45	0.55	0.70	0.79
10	0.44	0.54	0.74	0.81
11	0.39	0.51	0.67	0.82
$\bar{X}$	0.40	0.51	0.67	0.71
SD	0.06	0.05	0.06	0.08
CV,%	15.0	0.10	9.0	11.3

* Mean
† Standard deviation
¥ Coefficient of variation

During the period 15 September - 9 October 1986, there was no statistically significant differences among the geometric mean densities of total coliforms in the influent to and the effluents from both digesters. This lack of statistically significant differences in total coliform geometric mean densities appears attributable to the abnormally high degree of variability in influent total coliform

TABLE 14. COMPARISONS OF INFLUENT AND EFFLUENT DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES FOR THE SAMPLING PERIOD 6 NOVEMBER - 5 DECEMBER 1985.

	Log_{10} CFU*/100 mL Mean ± Standard Deviation		
	Influent	Effluent# 20 days, 15°C	Effluent§ 20 days, 38°C
Total coliforms	$6.70^{a\dagger}$ ± 0.61	5.43^{b} ± 0.20	4.15^{c} ± 0.33
Fecal coliforms	5.65^{a} ± 0.41	4.64^{b} ± 0.38	3.23^{c} ± 0.68
Fecal streptococci	4.75^{a} ± 0.19	3.68^{b} ± 0.35	3.15^{c} ± 0.29
Enteroviruses¥	3.16^{a} ± 0.11	2.21^{b} ± 0.16	0.00^{c} ± 0.00

*Colony-forming units
†Means in the same row with a common superscript are not significantly different (P<0.05)
¥Plaque-forming units
#Conventional digester
§Autoheated digester

TABLE 15. COMPARISONS OF INFLUENT AND EFFLUENT DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES FOR THE SAMPLING PERIOD 6 JANUARY - 30 JANUARY 1986.

	Log_{10} CFU*/100 mL Mean ± Standard Deviation		
	Influent	Effluent# 20 days, 8°C	Effluent§ 10 days, 31°C
Total coliforms	$6.08^{a\dagger}$ ± 0.34	5.40^{b} ± 0.21	5.24^{b} ± 0.66
Fecal coliforms	5.04^{a} ± 0.49	4.40^{b} ± 0.19	4.00^{b} ± 0.76
Fecal streptococci	4.35^{a} ± 0.53	4.02^{ab} ± 0.27	3.75^{b} ± 0.47
Enteroviruses¥	3.05^{a} ± 0.19	2.33^{b} ± 0.14	1.97^{c} ± 0.35

*Colony-forming units
†Means in the same row with a common superscript are not significantly different (P<0.05)
¥Plaque-forming units
#Conventional digester
§Autoheated digester

TABLE 16. COMPARISONS OF INFLUENT AND EFFLUENT DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES FOR THE SAMPLING PERIOD 9 APRIL - 13 MAY 1986.

	Log_{10} CFU*/100 mL Mean ± Standard Deviation		
	Influent	Effluent# 20 days, 18°C	Effluent§ 15 days, 40°C
Total coliforms	$6.29^{a\dagger}$ ± 0.24	4.59^{b} ± 0.21	4.09^{c} ± 0.49
πFecal coliforms	4.73^{a} ± 0.23	3.35^{b} ± 0.20	3.15^{b} ± 0.31
Fecal streptococci	4.22^{a} ± 0.25	3.05^{b} ± 0.40	2.99^{b} ± 0.27
Enteroviruses¥	2.33^{a} ± 0.14	1.35^{b} ± 0.13	0.00^{c} ± 0.00

*Colony-forming units
†Means in the same row with a common superscript are not significantly different (P<0.05)
¥Plaque-forming units
#Conventional digester
§Autoheated digester

TABLE 17. COMPARISONS OF INFLUENT AND EFFLUENT DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES FOR THE SAMPLING PERIOD 28 JULY - 3 SEPTEMBER 1986.

	Log_{10} CFU*/100 mL Mean ± Standard Deviation	
	Influent	Effluent# 20 days, 26°C
Total coliforms	$5.51^{a\dagger}$ ± 0.31	4.08^{b} ± 0.19
Fecal coliforms	3.82^{a} ± 0.41	3.26^{b} ± 0.20
Fecal streptococci	3.73^{a} ± 0.34	3.01^{b} ± 0.52
Enteroviruses¥	3.32^{a} ± 0.16	2.04^{b} ± 0.06

*Colony-forming units
†Means in the same row with a common superscript are not significantly different (P<0.05)
¥Plaque-forming units
#Conventional digester

TABLE 18. COMPARISONS OF INFLUENT AND EFFLUENT DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES FOR THE SAMPLING PERIOD 15 SEPTEMBER - 9 OCTOBER 1986.

	Log_{10} CFU*/100 mL Mean ± Standard Deviation		
	Influent	Effluent# 20 days, 22°C	Effluent§ 10 days, 36°C
Total coliforms	$5.31^{a\dagger}$ ± 1.06	4.62^{a} ± 0.76	4.41^{a} ± 0.97
Fecal coliforms	4.64^{a} ± 0.69	3.46^{b} ± 0.95	3.54^{b} ± 0.52
Fecal streptococci	3.94^{a} ± 0.24	2.94^{b} ± 0.33	3.12^{b} ± 0.33
Enteroviruses¥	3.00^{a} ± 0.13	2.15^{b} ± 0.09	0.57^{c} ± 0.69

*Colony-forming units
†Means in the same row with a common superscript are not significantly different (P<0.05)
¥Plaque-forming units
#Conventional digester
§Autoheated digester

TABLE 19. COMPARISONS OF INFLUENT AND EFFLUENT DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES FOR THE SAMPLING PERIOD 2 FEBRUARY - 26 MARCH 1987.

	Log_{10} CFU*/100 mL Mean ± Standard Deviation		
	Influent	Effluent# 20 days, 24°C	Effluent§ 15 days, 29°C
Total coliforms	$6.72^{a\dagger}$ ± 0.55	4.61^{b} ± 0.50	5.28^{c} ± 0.50
Fecal coliforms	4.84^{a} ± 0.60	3.10^{b} ± 0.36	3.52^{b} ± 0.22
Fecal streptococci	4.54^{a} ± 0.45	3.12^{b} ± 0.34	3.74^{c} ± 0.43
Enteroviruses¥	2.47^{a} ± 0.36	1.41^{b} ± 0.45	1.45^{b} ± 0.61

*Colony-forming units
†Means in the same row with a common superscript are not significantly different (P<0.05)
¥Plaque-forming units
#Conventional digester
§Autoheated digester

densities (Table 18) during this period of steady-state operation. The reason or reasons for the high degree of variability in influent total coliform densities during this time period is unclear.

As can be seen in Table 20, a number of general patterns are readily discernible when the observed mean reductions in the three groups of indicator organisms and the enterovirus group of viruses are summarized. One is the differences in resistance to destruction among these four groups of microorganisms. Generally, total coliforms were the most easily destroyed while fecal streptococci were the most resistant. Reduction of enteroviruses were comparable to total coliforms in some situations but comparable to fecal streptococci in other instances. Similar similarities and differences have been observed in other studies involving both aerobic (Farrah et al, 1986 and Appleton et al, 1986) and anaerobic (Berg and Berman, 1980) sludge digestion.

These observations led to the examination of the nature of the relationships among these four groups of microorganisms with respect to reductions during aerobic digestion of wastewater treatment sludges. Again the question of statistical independence was of specific interest. As the observed geometric mean reductions for each group of microorganisms were found to be normally distributed ($P<0.01$) using the Kolmogorov - Smirnov test (Roghati, 1976), it was again possible to use correlation analyses (DeVore, 1982) to test for linear independence. The results of these correlation analyses are summarized in Table 21.

When the results of these correlation analyses are compared with the results of the raw sludge correlation analyses (Table 12), a number of similarities are apparent. One is the strength of the correlations between fecal coliforms and fecal streptococci. Another is the lack of strong correlations between the enterovirus group of viruses and each of three groups of indicator organisms although the correlations for reductions were stronger. A notable difference is the stronger correlation between reductions in total coliforms and fecal coliforms.

From the data summarized in Table 20, it also can be seen that both residence time and temperature appear to be important factors in the reduction of each of the three groups of indicator organisms. Residence time appears to be of lesser importance, however, as compared to temperature with respect to reductions in enterovirus densities. This becomes even more apparent when the observed reductions are ordered with respect to temperature (Table 22) and analyzed statistically. No linear or more accurately intrinsically linear probabilistic relationships between temperature and the observed reductions for each of the three groups of indicator organisms are readily discernible. This is confirmed by the values of the correlation coefficients for the linear regressions of the $\log_{10}$ reductions in the densities of total coliforms, fecal coliforms, and fecal streptococci on temperature which are 0.45, 0.53, and 0.39, respectively. These values suggest weak linear relationships and plots of standardized residuals do not suggest that non-linear probabilistic relationships would be more appropriate.

In contrast to each of the three groups of indicator organisms, there does appear to be an intrinsically linear probabilistic relationship between enterovirus reductions and temperature (Figure 17) as suggested by the moderately strong correlation coefficient, 0.81. Using the Student's t distribution with n-2 degrees of freedom, the null hypothesis that $\rho=0$ was rejected ($P<0.01$). Also, a plot of standardized residuals shows no unusual pattern which might indicate that a nonlinear relationship would be more appropriate.

The apparent dependence of reductions in the densities of the three groups of indicator organisms on both residence time and temperature becomes readily discernable when reductions are first grouped by residence time and then ordered with respect to temperature (Table 23). Interestingly, the same pattern of increasing reductions with increases in temperature for each residence time also applies to the enteroviruses. This apparent dependence of the reductions in the

TABLE 20. SUMMARY OF OBSERVED REDUCTIONS IN THE DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES DURING AUTOHEATED AND CONVENTIONAL AEROBIC DIGESTION

Digester	Residence time, days	Mixed liquor temperature, °C*	Reduction, log_{10} basis			
			Total coliforms	Fecal coliforms	Fecal streptococci	Enteroviruses
Autoheated	10	31.1 ± 1.2	0.84	1.04	0.60	1.08
	10	37.5 ± 1.3	0.90	1.10	0.82	2.43
	15	29.0 ± 1.5	1.44	1.32	0.80	1.03
	15	39.8 ± 2.4	2.20	1.58	1.23	2.33+
	20	38.2 ± 0.9	2.55	2.42	1.60	3.16+
Conventional	20	8.0 ± 1.6	0.68	0.64	0.33	0.72
	20	14.6 ± 2.1	1.27	1.01	1.07	0.95
	20	17.5 ± 2.3	1.70	1.38	1.17	0.98
	20	21.7 ± 2.0	0.69	1.18	1.00	0.85
	20	23.7 ± 1.1	2.11	1.74	1.42	1.06
	20	25.6 ± 1.8	1.43	0.56	0.72	1.28

*Mean ± Standard Deviation

densities of the three groups of indicator organisms and also possibly enteroviruses on both residence time and temperature suggested that it might be possible to describe these relationships mathematically using an Arrhenius type model. With such mathematical relationships, it would be possible to define values of residence time and temperature necessary for mesophilic aerobic digestion of sewage sludge to provide desired reductions in the densities of these four groups of microorganisms and by inference bacterial pathogens. In the following the formulation, testing, and validation of a set of mathematical models to describe these relationships are presented and discussed.

TABLE 21. RESULTS OF CORRELATION ANALYSES TO TEST FOR LINEAR INDEPENDENCE AMONG LOG_{10} REDUCTIONS OF TOTAL COLIFORMS, FECAL COLIFORMS, FECAL STREPTOCOCCI, AND ENTEROVIRUSES DURING AEROBIC DIGESTION.

Correlation	Correlation Coefficient, R
Total coliforms and fecal coliforms	0.793*
Total coliforms and fecal streptococci	0.838*
Total coliforms and enteroviruses	0.569†
Fecal coliforms and fecal streptococci	0.868*
Fecal coliforms and enteroviruses	0.650¥
Fecal streptococci and enteroviruses	0.512#

*Significantly different from $\rho=0$ ($P>0.99$)
†Not significantly different from $\rho=0$ ($\rho<0.05$)
¥Significantly different from $\rho=0$ ($P>0.95$)
#Not significantly different from $\rho=0$ ($P<0.10$)

As noted by Grady and Lim (1980), Arrhenius (1889) was the first to describe mathematically the effect of temperature on reactions. The equation Arrhenius proposed is:

$$k = A \exp(-u/RT) \quad (1)$$

where: k = the temperature dependent reaction-rate coefficient
A = constant
u = the temperature characteristic
R = the universal gas constant
T = the absolute temperature

Taking the natural logarithms of both sides of Equation 1 yields:

$$Ln(k) = -\frac{u}{R}\left(\frac{1}{T}\right) + Ln(A) \quad (2)$$

Thus, a plot of Ln(k) versus the reciprocal of absolute temperature should yield a straight line with slope -u/R and intercept Ln A. Once these parameters are determined using linear regression, the

reaction rate coefficient at any temperature, °K, can be determined directly using Equation 2.

TABLE 22. REDUCTIONS IN THE GEOMETRIC MEAN DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES ORDERED WITH RESPECT TO TEMPERATURE.

Mixed Liquor Temperature, °C	Log_{10} Reductions			
	Total Coliforms†	Fecal Coliforms*	Fecal Streptococci*	Enteroviruses
8.0	0.68	0.64	0.33	0.72
14.6	1.27	1.01	1.07	0.95
17.5	1.70	1.38	1.17	0.98
21.7	0.69	1.18	1.00	0.85
23.7	2.11	1.74	1.42	1.06
25.6	1.43	0.56	0.72	1.28
29.0	1.44	1.32	0.80	1.03
31.1	0.84	1.04	0.60	1.08
37.5	0.90	1.10	0.82	2.43
38.2	2.55	2.42	1.60	3.16
39.8	2.20	1.58	1.23	2.33

*Colony-forming units per 100 ml basis.
†Plaque-forming units per 100 ml basis.

If one assumes that the Arrhenius equation does describe the temperature dependence of a reaction, Equation 2 also can be used to determine the nature of that reaction. As previously discussed, a plot of the natural logarithms of temperature dependent reaction rate coefficients versus the reciprocals of absolute temperature should yield a straight line if the assumed nature of the reaction is correct. Thus, assumptions regarding the nature of reactions can be tested statistically using the strength of the correlation coefficient associated with the "best fit" linear regression equation describing the relationship between the two variables as a quantitative measure. This approach for determining the nature of temperature dependent reactions is valid, however, only if the dependent variables, the natural logarithms of the reaction rate coefficients, are normally distributed (Steel and Torrie, 1980).

Initially, it was assumed that the observed reductions in the densities of each of the three groups of indicator organisms and the enterovirus group of viruses could be characterized as either zero-order or first-order reactions. Thus, the following relationships (Levenspiel, 1972) were used to calculate zero-order (Equation 3) and first-order (Equation 4) reaction rate coefficients.

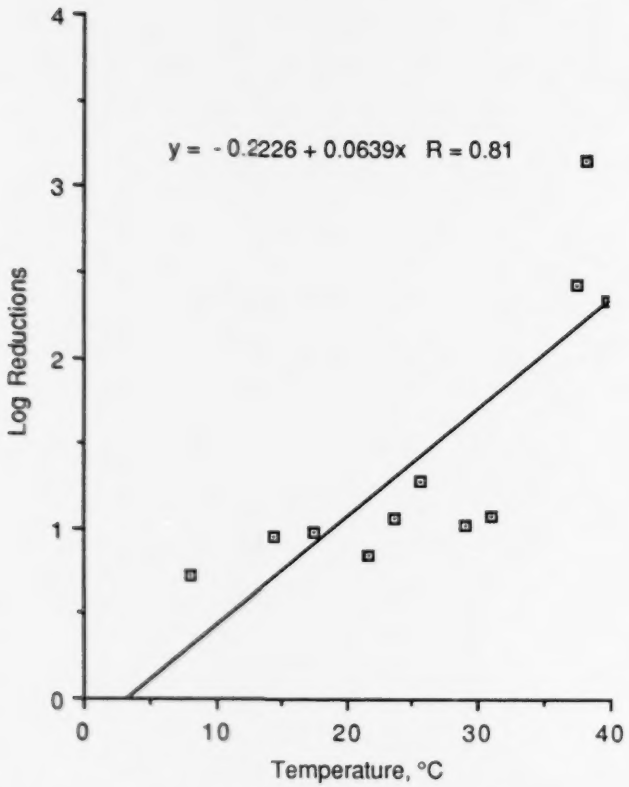

Figure 17. Enterovirus reductions, $\log_{10}$ basis, as a function of mixed liquor temperature.

$$k_o = \frac{S_o - S_1}{\theta} \qquad (3)$$

where: k_o = the zero-order reaction rate coefficient, CFU or PFU per 100 mL per day.
S_o = geometric mean influent microorganism density, CFU or PFU per 100 mL.
S_1 = geometric mean effluent microorganism density, CFU or PFU per 100 mL.
θ = residence time, days

$$k_1 = \frac{S_o - S_1}{S_1(\theta)} \qquad (4)$$

where: k_1 = The first-order reaction rate coefficient, $days^{-1}$

Although both digesters were operated as draw and fill reactors with daily sludge withdrawals and additions, as previously stated, it was assumed for the purpose of simplicity that the mathematical relationships defining zero and first-order reaction rate coefficients for a continuous-flow stirred tank reactor (CSTR) would provide reasonable approximations.

Using Equations 3 and 4, zero-order and first-order reaction rate coefficients for each period of steady-state operation were calculated using the antilogarithms (geometric means) of influent and effluent microorganism densities (Tables 14 through 19). Microorganism densities on a volumetric, per 100 mL, basis rather than on a per gram of total solids basis were used to eliminate the influence of total solids as an added variable.

When the natural logarithms of the calculated zero-order and first-order reaction rate coefficients for each group of microorganisms were plotted versus the reciprocals of absolute temperature, there was no visual evidence of strong or even moderately strong linear relationships for any of the four groups of microorganisms. These results could be interpreted to suggest the conclusion that the reductions in the densities of indicator organisms and enteroviruses during aerobic sludge digestion can not be characterized as either zero-order or first-order reactions. Such a conclusion only should be considered as tentative, however, given the characteristics of the data bases used for these analyses. Due to the magnitudes and the ranges of the geometric means of both influent and effluent densities for each group of microorganisms and the relatively limited number of independent observations, normal distributions as determined by the Kolmogorov-Smirnov test (Rohatgi, 1976) were lacking. Also, the natural logarithms of both the zero-order and first-order reaction rate coefficients were not normally distributed precluding the use of regression and correlation analyses.

The failure of both the zero-order and first-order Arrhenius type models to describe the temperature dependence of the microbial reductions observed in this study led to the formulation of a simple empirical rate equation (Equation 5) as an alternative.

$$k = \frac{S_e - S_i}{\theta} \qquad (5)$$

where: k = the empirical reaction rate coefficient, Log_{10} reduction per day.
S_i = influent microorganism density, Log_{10} CFU or PFU per 100 mL.
S_e = effluent microorganism density, Log_{10} CFU or PFU per 100 mL.
θ = residence time, days

Base 10 logarithms of both influent and effluent microorganism densities for each group of

microorganisms were used to normalize these data sets. Again, microorganism densities on a volumetric, per 100 mL, basis were used to eliminate the influence of total solids reductions as an added variable.

TABLE 23. REDUCTIONS IN THE GEOMETRIC MEAN DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES GROUPED BY RESIDENCE TIME AND THEN ORDERED WITH RESPECT TO TEMPERATURE.

		Log_{10} Reductions			
Residence Time, Days	Mixed Liquor Temperature, °C	Total Coliforms*	Fecal Coliforms*	Fecal Streptococci*	Enteroviruses†
10	31.1	0.84	1.04	0.60	1.08
	37.5	0.90	1.10	0.82	2.43
15	29.0	1.44	1.32	0.80	1.03
	39.8	2.20	1.58	1.23	2.33
20	8.0	0.68	0.64	0.33	0.72
	14.6	1.27	1.01	1.07	0.95
	17.5	1.70	1.38	1.17	0.98
	21.7	0.69	1.18	1.00	0.85
	23.7	2.11	1.74	1.42	1.06
	25.6	1.43	0.56	0.72	1.28
	38.2	2.55	2.42	1.60	3.16

*Colony-forming units per 100 mL basis.
†Plaque-forming units per 100 mL basis.

Using Equation 5, empirical reaction rate coefficients for each period of steady-state operation were calculated for each of the three groups of indicator organisms and the enterovirus group of viruses using the logarithmic means of influent and effluent densities presented in Tables 14 through 19. The results of these calculations are summarized in Table 24.

When the natural logarithms of the empirical reaction rate coefficients for the total coliform, fecal coliform, and fecal streptococcus groups of bacteria and the enterovirus group of viruses were plotted versus the reciprocals of absolute temperature (Figures 18, 19, 20, and 21 respectively), the anticipated linear relationships were realized. The natural logarithms of the empirical reaction rate

coefficients for each group of microorganisms were found to be normally distributed using the Kolmogorov-Smirnov test (Rohatgi, 1976). Thus, it was possible to use correlation coefficients associated with "best fit" linear regression equations determined using the least squares method (Devore, 1982) to quantify the strengths of these linear relationships and therefore test the validity of the proposed empirical model.

TABLE 24. SUMMARY OF EMPIRICAL MODEL REACTION RATE COEFFICIENTS FOR REDUCTIONS IN THE DENSITIES OF THE THREE GROUPS OF INDICATOR ORGANISMS AND THE ENTEROVIRUSES.

Residence Time, Days	Mixed Liquor Temperature, °C	Empirical Model Reaction Rate Coefficients*			
		Total Coliforms	Fecal Coliforms	Fecal Streptococci	Enteroviruses
20	8.0	0.03	0.03	0.03	0.04
20	14.6	0.06	0.05	0.05	0.05
20	17.5	0.08	0.07	0.06	0.05
20	21.7	0.03	0.06	0.05	0.04
20	23.7	0.11	0.09	0.07	0.05
20	25.6	0.07	0.03	0.04	0.06
15	29.0	0.10	0.09	0.05	0.07
10	31.1	0.08	0.10	0.06	0.11
10	37.5	0.09	0.11	0.08	0.24
20	38.2	0.13	0.12	0.08	0.16
15	39.8	0.15	0.11	0.08	0.16

*CFU OR PFU per 100 mL per day.

The results of the regression and associated correlation analyses for the empirical model reaction rate coefficients are presented in Figures 18 through 21. Examination of these empirical model Arrhenius plots for total coliforms, fecal coliforms, and fecal streptococci (Figures 18 through 20) and the associated values of standardized residuals (Table 25) suggested the possible presence of discrepant or outlying observations in these data sets. Specifically, the reaction rate coefficients for total coliforms at 21.7°C and fecal coliforms and fecal streptococci at 25.6°C (Table 24) appeared to be suspect. All three of these reaction rate coefficients have standardized residuals lying outside the interval of -2 to +2.

No assignable causes such as errors in analytical methodology, recording of data, or subsequent calculations could be identified to explain the presence of these apparently discrepant observations. Thus, the statistical methodology outlined by Snedecor and Cochran (1980) for testing

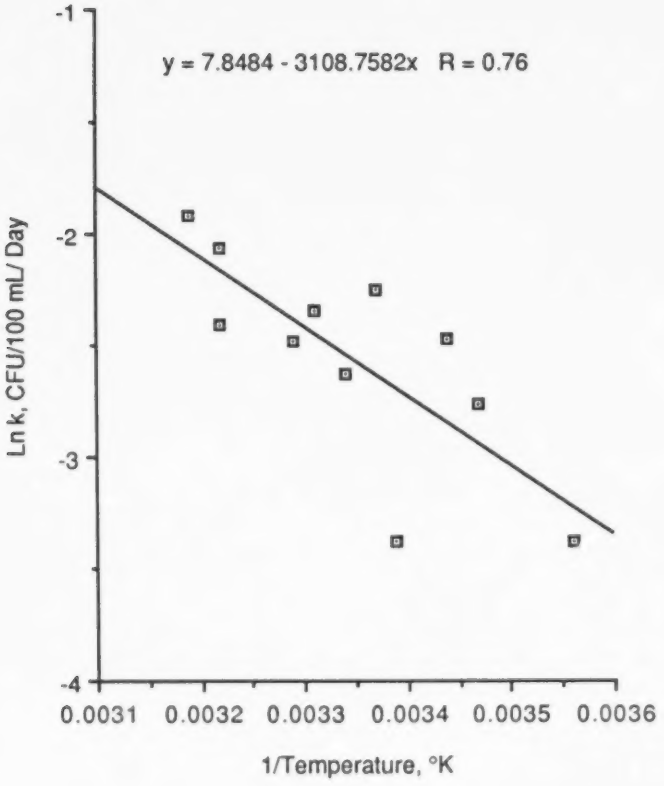

Figure 18. Empirical model Arrhenius plot for total coliforms, CFU/100 mL basis.

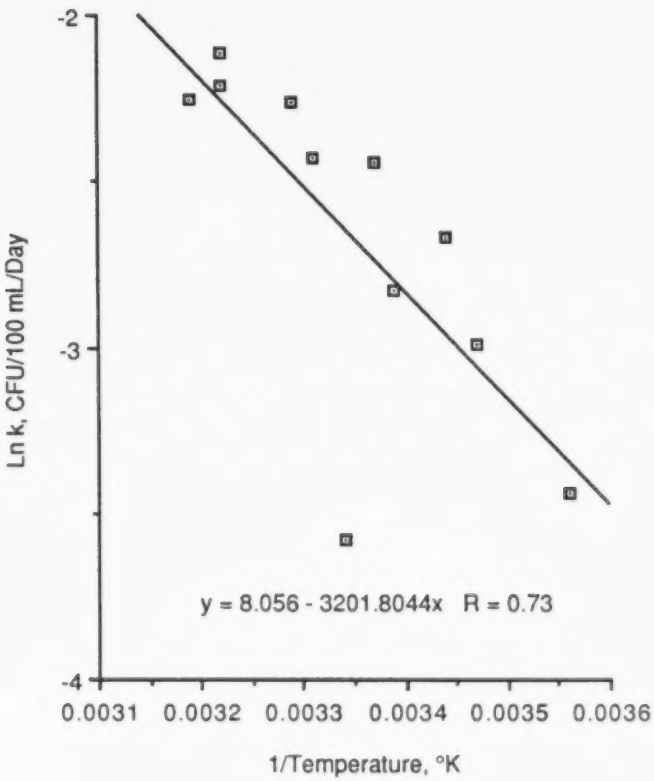

Figure 19. Empirical model Arrhenius plot for fecal coliforms, CFU/100 mL basis.

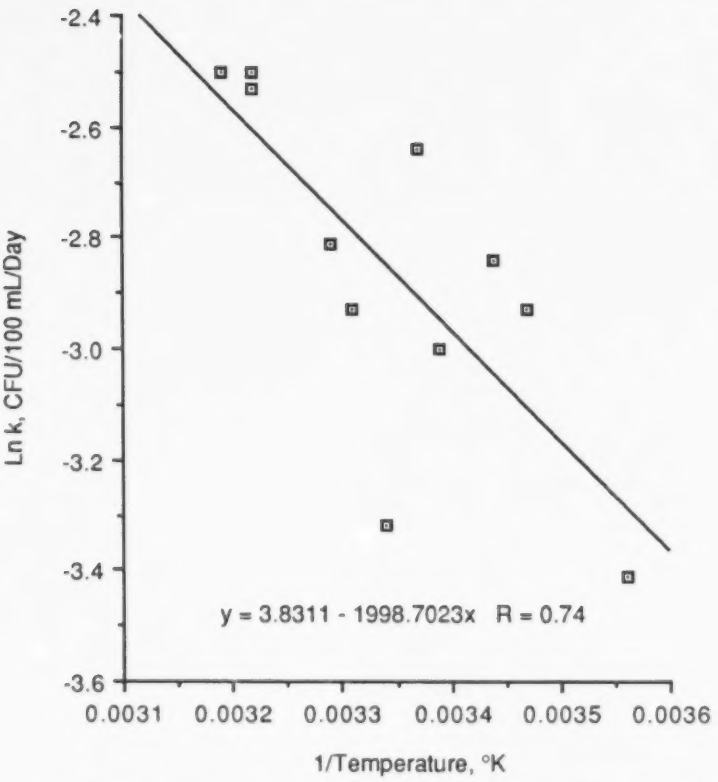

Figure 20. Empirical model Arrhenius plot for fecal streptococci, CFU/100 mL basis.

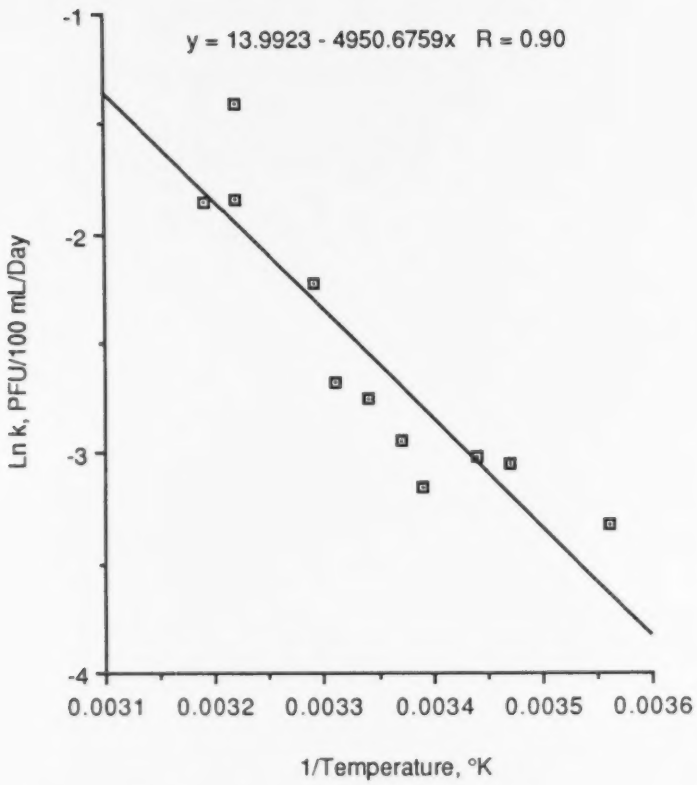

Figure 21. Empirical model Arrhenius plot for enteroviruses, PFU/100 mL basis.

suspiciously large deviations in regression analysis was used to test the validity of these observations. This methodology uses the Student's t distribution to calculate the probability that a random value will have a deviation exceeding the deviation of the extreme observation. The results of these calculations indicated that all of the observations considered to be suspect were unusual. For the empirical Arrhenius model, the calculated probabilities that random values for total coliforms, fecal coliforms, and fecal streptococci would have deviations exceeding the extreme observations were 0.23, <0.01, and 0.18 respectively. In contrast, all of the calculated probabilities for the reaction-rate coefficients with the second highest standardized residuals, absolute values, exceeded 0.90. Therefore, all three of the suspect reaction rate coefficients were judged to be invalid.

TABLE 25. EMPIRICAL MODEL STANDARDIZED RESIDUALS FOR TOTAL COLIFORM, FECAL COLIFORM, FECAL STREPTOCOCCI, AND ENTEROVIRUS ARRHENIUS PLOT LINEAR REGRESSIONS.

		Standardized Residuals			
Residence Time, Days	Mixed Liquor Temperature, °C	Total Coliforms	Fecal Coliforms	Fecal Streptococci	Enteroviruses
20	8.0	-0.50	-0.27	-0.58	1.08
20	14.6	0.56	0.18	0.80	0.47
20	17.5	1.17	0.80	0.93	0.06
20	21.7	-2.12	-0.09	-0.25	-1.28
20	23.7	1.18	0.82	1.21	-0.86
20	25.6	-0.30	-2.62	-2.17	-0.72
15	29.0	0.32	0.31	-0.66	-0.99
10	31.1	-0.31	0.61	-0.30	0.23
10	37.5	-0.77	0.12	0.48	1.87
20	38.2	0.32	0.40	0.34	0.34
15	39.8	0.46	0.26	0.20	-0.21

The results of the empirical model linear regression and associated correlation analyses for total coliforms, fecal coliforms, and fecal streptococci without those previously identified reaction-rate coefficients judged to be invalid are presented in Figures 22 through 24. In Table 26, the results of the linear regression and correlation analyses without the previously discussed outlying values are summarized and compared. As indicated by the noted correlation coefficients, the strength of the linear relationships between reaction rate coefficients and the reciprocals of absolute temperature are universally strong for the empirical model.

This effort to model the reductions of indicator organisms and enteroviruses during aerobic sludge digestion would not be complete without the process of model validation. In order to locate

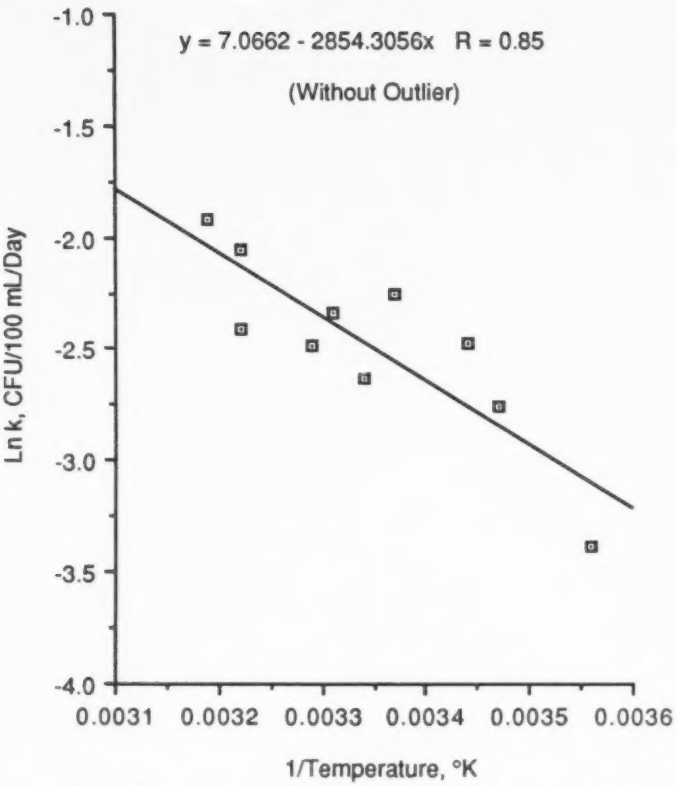

Figure 22. Empirical model Arrhenius plot without outlier for total coliforms, CFU/100 mL basis.

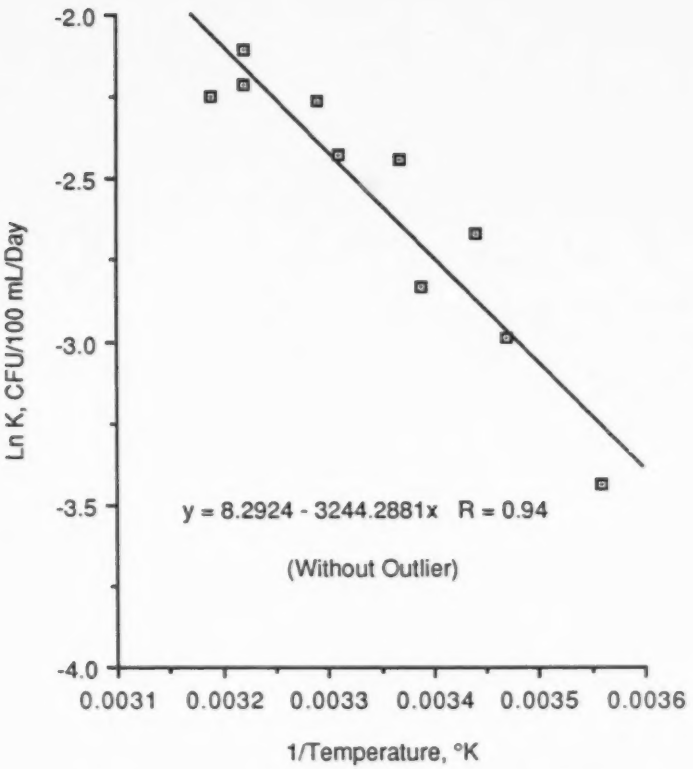

Figure 23. Empirical model Arrhenius plot without outlier for fecal coliforms, CFU/100 mL basis.

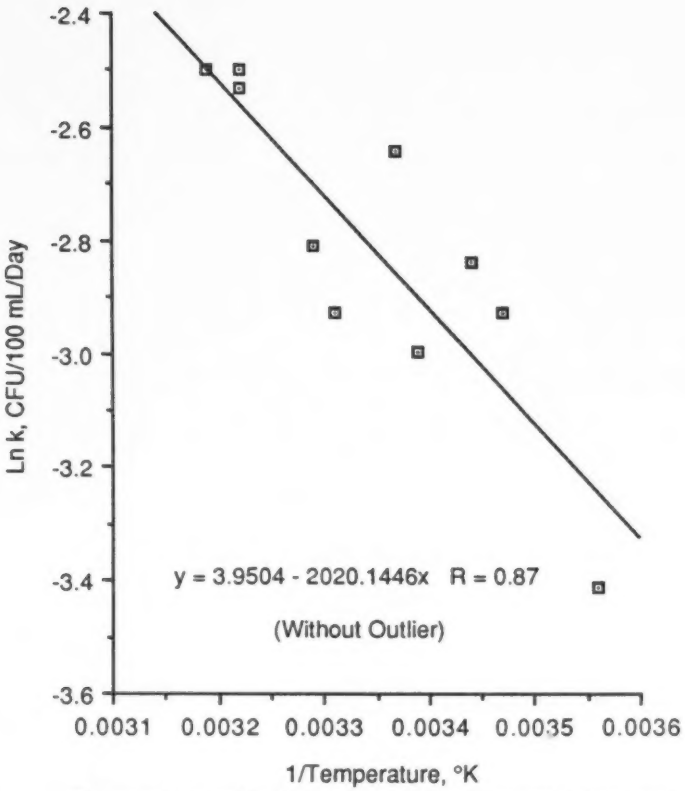

Figure 24. Empirical model Arrhenius plot without outlier for fecal streptococci, CFU/100 mL basis.

the data necessary for this process, a review of the pertinent literature was conducted with only limited success. Only two sets of suitable data were identified. The first is from a study of aerobic sludge digestion conducted by Kuchenrither (1981) and also summarized by Kuchenrither and Benefield (1983) and the second is from a similar study conducted by Farrah et al. (1986). Both of these studies were comparable to the study being described and discussed in this report in that both mixed liquor residence time and temperature were variables with similar ranges of values. An important difference, however, is the difference in scale. The studies by both Kuchenrither and Farrah et al. were laboratory studies while this study was a field study.

TABLE 26. SUMMARY OF LINEAR REGRESSION AND CORRELATION ANALYSES RESULTS FROM THE EMPIRICAL MODEL ARRHENIUS PLOTS.

Empirical model	Regression equation	Correlation coefficient
Total coliforms	Ln k = 7.0662 - 2854.3056 X	0.85
Fecal coliforms	Ln k = 8.2924 - 3244.2881 X	0.94
Fecal streptococci	Ln k = 3.9504 - 2020.1446 X	0.87
Enteroviruses	Ln k = 13.9923 - 4950.6759 X	0.90

Unfortunately, neither of these two data sets is as complete as would be desired for determining the validity of the proposed empirical model for describing the relationships between residence time and temperature and reductions in the three groups of indicator organisms and the enteroviruses during aerobic sludge digestion. For example, neither Kuchenrither nor Farrah et al. reported total coliform reductions. In addition, only Farrah et al. determined virus reductions and then only for one member of the enterovirus group, poliovirus. In spite of these limitations, both of these data sets were of value in assessing the validity of the proposed modeling approaches as will be demonstrated.

As shown in Tables 27 and 28, there appears to be a reasonable degree of agreement between the empirical model reaction rate coefficients predicted by the regression equations for both fecal coliforms and fecal streptococci (Table 26) and the values calculated from the data reported from the two earlier studies. From the comparisons presented in these tables (Tables 27 and 28) it can be, at least, tentatively concluded that the relationships between residence time and temperature and reductions in the densities of fecal coliforms and fecal streptococci can be best described by the empirical model. Also, this tentative conclusion can be extended by inference for total coliforms if one assumes Enterobacter aerogenes densities are constant since fecal coliforms are a component of the total coliform group. Unfortunately, the only evidence available to assess the validity of the empirical model for enteroviruses is the correlation coefficients associated with the regression analyses. As noted in Table 26, the correlation coefficients for the empirical Arrhenius model for enteroviruses was 0.90. Thus, it can be concluded, at least for this study, that this empirical model can be used to mathematically describe the observed relationship between mixed liquor temperature and residence time and reduction of enterovirus density during aerobic sludge digestion.

The objective of this mathematical modeling exercise was to develop a methodology for determining the residence time necessary for a given mixed liquor temperature that will provide a desired reduction in the densities of the three groups of indicator organisms and the enterovirus group of viruses during aerobic sludge digestion. In Table 29, the residence times calculated, using

TABLE 27. COMPARISON OF PREDICTED EMPIRICAL MODEL REACTION RATE COEFFICIENTS FOR FECAL COLIFORMS WITH VALUES REPORTED BY KUCHENRITHER (1981) AND FARRAH ET AL. (1986).

Temperature, °C	Empirical reaction rate coefficients	
	Predicted*	Observed by others
6	0.04	0.02†
20	0.06	0.08†, 0.05 ± 0.02¥
27	0.08	0.03†, 0.08†
28	0.08	0.08†
30	0.09	0.11 ± 0.01¥

*From regression equation
†Farrah et al. (1986)
¥Kuchenrither (1981) (n=6)

TABLE 28. COMPARISON OF PREDICTED EMPIRICAL MODEL REACTION RATE COEFFICIENTS FOR FECAL STREPTOCOCCI WITH VALUES REPORTED BY KUCHENRITHER (1981) AND FARRAH ET AL. (1986).

Temperature, °C	Empirical reaction rate coefficients	
	Predicted*	Observed by others
6	0.04	>0.01†
20	0.05	0.08†, 0.03 ± 0.01¥
27	0.06	0.02†, 0.02†
28	0.06	0.05†
30	0.07	0.05 ± 0.02¥
40	0.08	0.11 ± 0.01¥

*From regression equation
†Farrah et al (1986)
¥Kuchenrither (1981) (n=6)

TABLE 29. EFFECT OF TEMPERATURE ON RESIDENCE TIMES REQUIRED FOR TWO LOG_{10} REDUCTIONS IN THE DENSITIES OF THE THREE GROUPS OF INDICATOR ORGANISMS AND ENTEROVIRUSES DURING AEROBIC DIGESTION AS PREDICTED BY THE ZERO-ORDER ARRHENIUS MODEL EQUATIONS.

	Residence time required for two log_{10} reductions, days					
	5 °C	10 °C	15 °C	20 °C	30 °C	40 °C
Total coliforms	50	40	33	29	22	15
Fecal coliforms	67	50	40	33	22	15
Fecal streptococci	50	50	40	40	29	25
Enteroviruses	100	67	50	40	20	12

Equation 5 and the empirical model equations (Table 26), to be necessary to provide two $\log_{10}$ reductions are presented. As shown in Table 29, even a modest 10°C increase in mixed liquor temperature generally results in a significant reduction in required residence time and thus, aeration basin volume. It is interesting that the residence times of 60 days at 15°C to 40 days at 20°C specified for aerobic digestion in Section 257.3-6 of 40 CFR 257 (U.S. Code of Federal Regulations, 1979) have predicted reductions of at least two $\log_{10}$ in the densities of the indicator and enteroviruses.

Sludge Stabilization

In this investigation, reduction in concentrations of total solids, total volatile solids, chemical oxygen demand, and organic nitrogen were used as the parameters to characterize digester performance with respect to sludge stabilization. Mean reductions in these physical and chemical parameters during periods of autoheated and conventional digester steady-state operation are summarized and compared statistically in Tables 30 and 31, respectively. One-way analysis of variance (Snedecor and Cochran, 1980) followed by Fisher's protected least significant difference test (Steel and Torrie, 1980) was used to perform these statistical comparisons. The mean reductions presented in these tables were calculated from means of influent and effluent sludge analyses for each period of steady-state operation which are presented in Appendix C, Tables C-1 through C-11.

As shown in Tables 30 and 31, the observed reductions for each of the four parameters used to characterize sludge stabilization generally fell into relatively narrow ranges of values. Also, there was no readily discernable patterns of increasing reductions with increases in residence time and mixed liquor temperature as would be expected.

In theory, unstabilized sewage sludge should contain only an insignificant amount of soluble biodegradable organic matter. Thus, the only reactions occurring should be cellular death and decay which can be represented by a first-order rate equation. As noted by Grady and Lim (1980), this first-order depiction of aerobic digestion is widely accepted in the literature. In addition, it should be possible to quantify the effect of temperature on first-order reaction rate coefficients using the previously discussed Arrhenius equation (Equation 1). When the linearized form of the Arrhenius equation (Equation 2) is used, a plot of Ln(k) versus the reciprocal of absolute temperature should yield a straight line with slope -u/R and intercept A as previously noted.

When the natural logarithms of first-order reaction rate coefficients for total volatile solids, chemical oxygen demand, and organic nitrogen calculated from the results obtained in this study (Table 32) are plotted versus the reciprocals of absolute temperature (Figures 25, 26, and 27, respectively), the absence of the anticipated strong linear relationships is obvious. The first-order reaction rate coefficients presented in Table 32 were calculated (Equation 4) using mean influent and effluent concentrations for each period of steady-state operation which are summarized in Appendix C, Tables C-1 through C-11. As indicated by the noted values of the correlation coefficients (Figures 25 through 27) associated with the "best fit" linear regression equations determined using the least squares method (Devore, 1982), changes in temperature only partially explain the observed changes in the first-order reaction rate coefficients for each of these three parameters.

The factor or factors responsible for this apparent failure of the first-order Arrhenius model to describe the effect of temperature on reaction rate coefficients calculated from the results obtained in this study is unclear. Several possible factors were considered. One, the absence of adequate dissolved oxygen concentrations was immediately discounted. As discussed earlier, mixed liquor dissolved oxygen concentrations in both digesters were routinely determined. Residual concentrations were never less than 0.5 mg/L and normally were in excess of 1 mg/L.

TABLE 30. SUMMARY OF OBSERVED CHANGES IN SLUDGE PHYSICAL AND CHEMICAL CHARACTERISTICS DURING AUTOHEATED AEROBIC DIGESTION.

Residence time, days	Mixed liquor temperature, °C	Reduction, percent			
		Total solids	Total volatile solids	Chemical oxygen demand	Organic nitrogen
10	31.1* ± 1.2	29.8[a]† ± 3.4	37.6[a] ± 3.5	40.5[a] ± 4.1	32.2[a] ± 3.5
10	37.5 ± 1.3	28.8[a] ± 3.5	37.2[a] ± 4.5	41.4[a] ± 7.6	45.8[b] ± 6.4
15	29.0 ± 1.5	25.7[b] ± 2.3	33.1[b] ± 3.0	37.6[a] ± 4.7	32.7[a] ± 4.9
15	39.8 ± 2.4	33.7[c] ± 3.4	40.1[a] ± 3.2	42.0[a] ± 8.4	38.0[c] ± 3.6
20	38.2 ± 0.9	26.8[ab] ± 3.2	38.3[a] ± 2.5	54.1[b] ± 4.5	55.4[d] ± 6.4

*Mean ± Standard Deviation

†Means in the same column with a common superscript are not significantly different ($P<0.05$).

TABLE 31. SUMMARY OF OBSERVED CHANGES IN SLUDGE PHYSICAL AND CHEMICAL CHARACTERISTICS DURING CONVENTIONAL AEROBIC DIGESTION.

Residence time, days	Mixed liquor temperature, °C	Reduction, percent			
		Total solids	Total volatile solids	Chemical oxygen demand	Organic nitrogen
20	8.0* ± 1.6	25.3[a†] ± 4.4	30.8[a] ± 4.4	37.7[a] ± 3.5	29.0[a] ± 4.0
20	14.6 ± 2.1	35.2[a] ± 4.8	42.9[a] ± 5.6	49.8[a] ± 4.9	45.3[bc] ± 6.2
20	17.5 ± 2.3	33.9[b] ± 2.6	41.9[b] ± 2.1	45.4[bc] ± 2.3	42.2[b] ± 2.0
20	21.7 ± 2.0	27.2[ac] ± 4.9	37.0[c] ± 6.5	43.7[c] ± 5.1	47.4[c] ± 2.0
20	23.7 ± 1.1	29.5[a] ± 3.0	41.5[b] ± 3.5	44.3[c] ± 5.4	42.1[b] ± 7.1
20	25.6 ± 1.8	26.2[a] ± 2.2	37.0[c] ± 2.8	44.0[c] ± 7.3	46.1[c] ± 2.8

*Mean ± Standard Deviation

†Means in the same column with a common superscript are not significantly different ($P<0.05$).

A second factor that was considered was differences in the biodegradable and refractory fractions of the four parameters used to characterize sludge stabilization among the periods of steady-state operation. Such differences could have resulted in substrate limitations during certain periods of steady-state operation. As previously discussed, the results of the batch biodegradability studies indicated that the estimated biodegradable and refractory fractions of the sludge used in this study did vary in an apparently random manner as was shown in Table 13. The estimated reductions in the biodegradable fractions of total solids, total volatile solids, chemical oxygen demand, and organic nitrogen summarized in Table 33 do not indicate, however, that substrate limitations were responsible for the apparent failure of the first-order Arrhenius model to describe the results obtained in this study. The estimated reductions of biodegradable fractions presented in Table 33 were calculated from the results of influent and effluent analyses summarized in Appendix C, Tables C-1 through C-11, using the mean values for the biodegradable fractions presented in Table 13.

TABLE 32. SUMMARY OF FIRST-ORDER REACTION RATE COEFFICIENTS FOR OBSERVED REDUCTIONS IN CONCENTRATIONS OF TOTAL VOLATILE SOLIDS, CHEMICAL OXYGEN DEMAND, AND ORGANIC NITROGEN.

Residence Time, Days	Mixed Liquor Temperature, °C	First-order reaction rate coefficients, $days^{-1}$		
		Total Volatile Solids	Chemical Oxygen Demand	Organic Nitrogen
20	8.0	0.022	0.030	0.021
20	14.6	0.038	0.050	0.042
20	17.5	0.036	0.042	0.037
20	21.7	0.030	0.039	0.045
20	23.7	0.036	0.041	0.038
20	26.0	0.030	0.040	0.043
15	29.0	0.033	0.041	0.033
10	31.0	0.061	0.069	0.048
10	37.5	0.060	0.072	0.087
20	38.2	0.031	0.060	0.064
15	39.8	0.045	0.050	0.041

The third factor that was considered as a possible explanation for the apparent failure of the first-order Arrhenius model to describe the relationships between mixed liquor temperature and the first-order reaction rate coefficients for the parameters used to characterize sludge stabilization in this study was validity of the assumption that unstabilized sewage sludge contains only an insignificant amount of soluble biodegradable organic matter. If this assumption is not valid, the first-order reaction rate coefficients calculated from the results obtained in this study were functions not only of residence time and temperature but also relative quantities of soluble and particulate biodegradable organics.

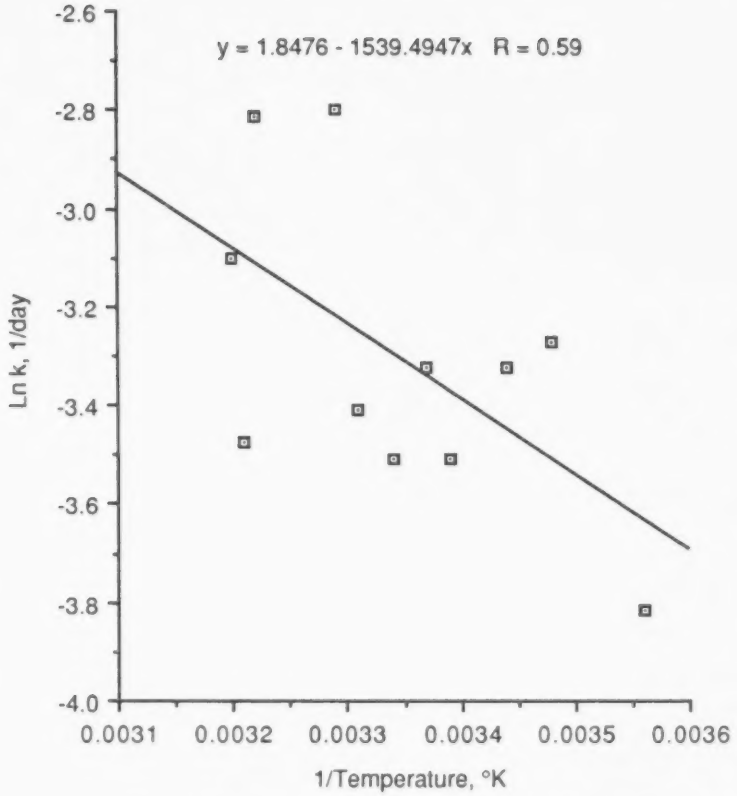

Figure 25. First-order Arrhenius plot for total volatile solids.

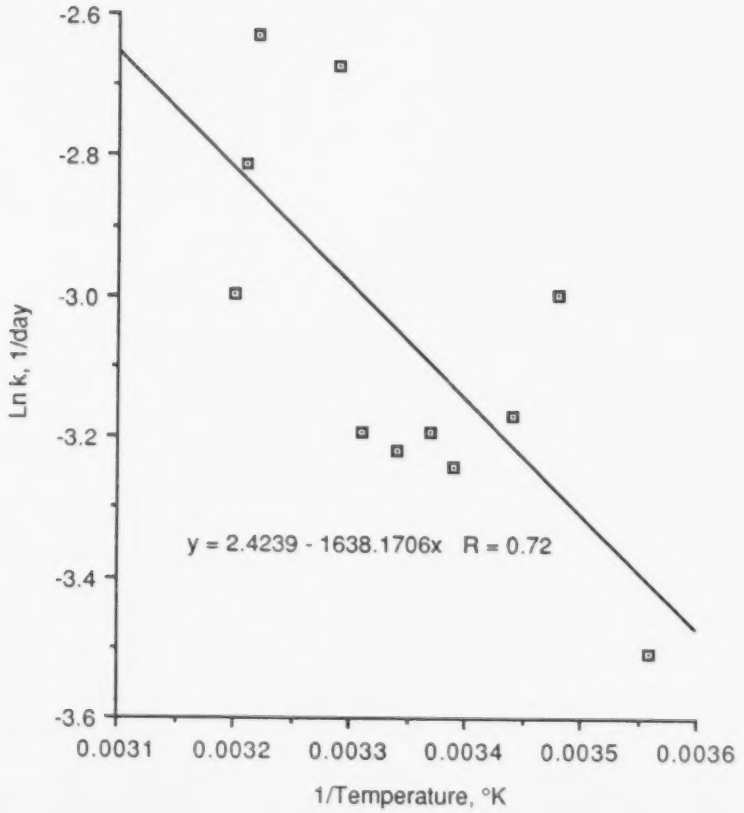

Figure 26. First-order Arrhenius plot for chemical oxygen demand.

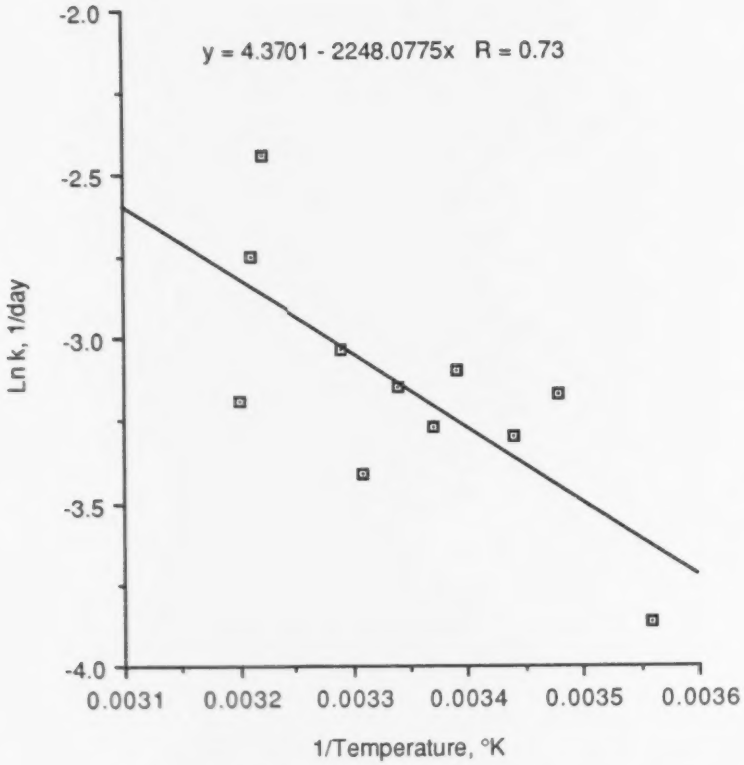

Figure 27. First-order Arrhenius plot for organic nitrogen.

TABLE 33. SUMMARY OF ESTIMATED REDUCTIONS IN BIODEGRADABLE FRACTIONS OF TOTAL SOLIDS, TOTAL VOLATILE SOLIDS, CHEMICAL OXYGEN DEMAND, AND ORGANIC NITROGEN DURING AUTOHEATED AND CONVENTIONAL AEROBIC DIGESTION.

Digester	Residence time, days	Mixed liquor temperature, °C	Biodegradable fraction reduction, percent			
			Total solids	Total volatile solids	Chemical oxygen demand	Organic Nitrogen
Autoheated	10	31.1 ± 1.2*	74.5 ± 8.4	73.6 ± 6.9	60.4 ± 6.1	46.0 ± 5.0
	10	37.5 ± 1.3	72.0 ± 8.8	73.0 ± 8.8	61.3 ± 11.3	65.5 ± 9.1
	15	29.0 ± 1.5	64.3 ± 5.7	64.9 ± 5.8	56.1 ± 7.1	46.7 ± 6.7
	15	39.8 ± 2.4	84.4 ± 8.0	78.6 ± 5.8	62.6 ± 11.9	54.3 ± 4.9
	20	38.2 ± 0.9	67.0 ± 8.0	75.1 ± 5.0	80.7 ± 6.8	79.1 ± 9.2
Conventional	20	8.0 ± 1.6	63.4 ± 10.9	60.4 ± 8.6	56.2 ± 5.3	41.4 ± 5.6
	20	14.6 ± 2.1	88.1 ± 12.0	84.0 ± 11.0	74.3 ± 7.4	64.8 ± 8.8
	20	17.5 ± 2.3	84.9 ± 6.6	82.2 ± 3.9	67.7 ± 3.2	60.2 ± 2.8
	20	21.7 ± 2.0	68.0 ± 12.4	72.4 ± 12.7	65.2 ± 7.6	67.8 ± 2.9
	20	23.7 ± 1.1	73.8 ± 7.2	81.4 ± 6.7	66.2 ± 7.9	60.2 ± 9.9
	20	25.6 ± 1.8	65.7 ± 5.6	72.5 ± 5.1	65.6 ± 10.5	65.5 ± 3.8

*Mean ± Standard Deviation

Since soluble organic matter is more readily available and thus more easily degraded than particulate organic matter, overall reaction rate coefficients will increase as the fraction of soluble biodegradable organics increases. Unfortunately, the soluble and particulate fractions of raw sludge total solids, total volatile solids, chemical oxygen demand, and organic nitrogen were not determined in this study. Thus, differences in the relative quantities of soluble and particulate biodegradable organics in the unstabilized sludge used in this study only can be proposed as a possible explanation for the lack of strong linear correlations between the natural logarithms of first-order reaction rate coefficients and reciprocals of absolute temperature shown in Figures 25 through 27.

Interestingly, strong linear relationships also are lacking when results from two similar studies are plotted in a similar manner. In Figures 28 and 29, first-order reaction rate coefficients for total volatile solids and chemical oxygen demand calculated from results reported by Jewell et al. (1982) for mixed liquor temperatures ranging from 47°C to 62°C are plotted. In Figure 30, first-order reaction rate coefficients for total volatile solids calculated from results reported by Appleton and Venosa (1986) for mixed liquor temperatures ranging from 48°C to 52°C are plotted. Unfortunately, Appleton and Venosa (1986) did not report influent and effluent chemical oxygen demand or organic nitrogen concentrations and Jewell et al. (1982) did not report influent and effluent organic nitrogen concentrations. Evidently, the same factor or factors responsible for the apparent failure of the first-order Arrhenius model to describe the relationships between temperature and first-order reaction rate coefficients in this study also were present in the studies conducted by Jewell et al. (1982) and Appleton and Venosa (1986).

Even more interesting, however, are the relationships that were obtained when the results from the three studies are combined. As shown in Figure 31, there is a strong linear relationship between the natural logarithms of first-order reaction rate coefficients for total volatile solids and the reciprocals of absolute temperature when results from this study are combined with results from the studies conducted by Jewell et al. (1982) and Appleton and Venosa (1986). The same is true for chemical oxygen demand (Figure 32) when the results from this study and the study conducted by Jewell et al. (1982) are combined. The results of these analyses (Figures 31 and 32), suggest that the unknown factor or factors discussed earlier as an explanation of the apparent failure of the first-order Arrhenius model to describe the relationship between mixed liquor temperature and sludge stabilization in this and other studies becomes less important as a variable as temperature range increases.

When the regression equations for total volatile solids and chemical oxygen demand (Figures 31 and 32) are used to calculate first-order reaction rate coefficients for temperatures ranging from 10°C to 60°C, it appears that the reaction rates for both parameters roughly double for every 20°C increase in mixed liquor temperature as shown in Table 34. Thus, it appears that aerobic digester residence time and thus, volume necessary to achieve a desired degree of sludge stabilization can be reduced approximately by a factor of two for every 20°C increase in mixed liquor temperature.

Estimated residence times necessary to achieve at least a 38 percent reduction in total volatile solids concentration as required by Section 257.3-6 of 40 CFR 257 (U.S. Code of Federal Regulations, 1979) calculated using the first-order reaction rate coefficients determined using the regression equations noted in Figures 31 and 32 and presented in Table 34 are outlined in Table 35. When the residence times required for a minimum of a 38 percent total volatile solids reduction at temperatures ranging from 10°C to 40°C are compared to the estimated residence times necessary for two $\log_{10}$ reductions in the densities of the three groups of indicator organisms and the enterovirus group of viruses (Table 29), it appears that the residence times necessary for this level of microbial reductions will insure the desired degree of sludge stabilization. At mixed liquor temperatures above 40°C, microbial reductions reported by Jewell et al. (1982) and Appleton and Venosa (1986) indicate that sludge stabilization may be the constraining factor in determining residence time.

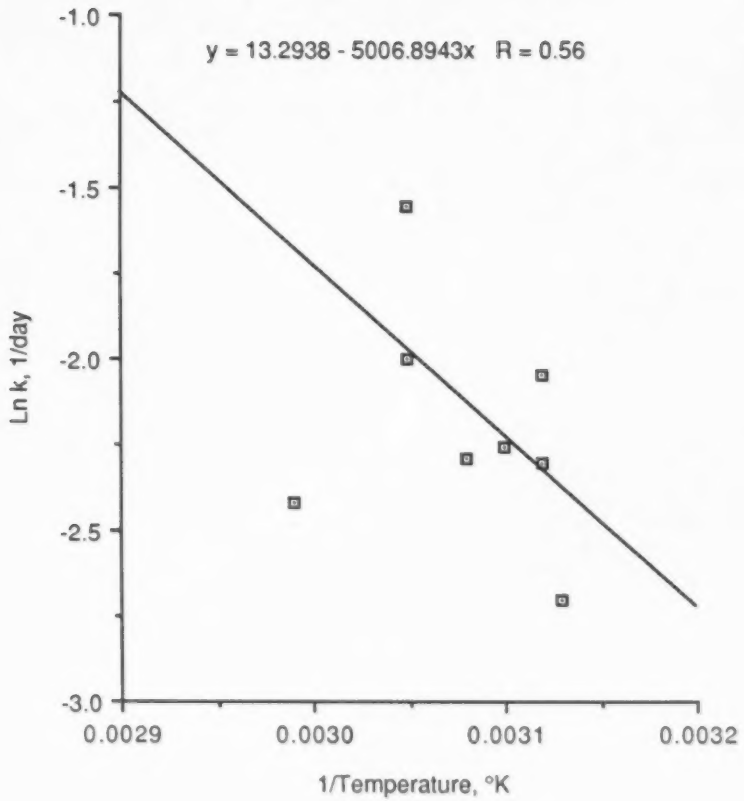

Figure 28. First-order Arrhenius plot for total volatile solids from data reported by Jewell et al. (1982).

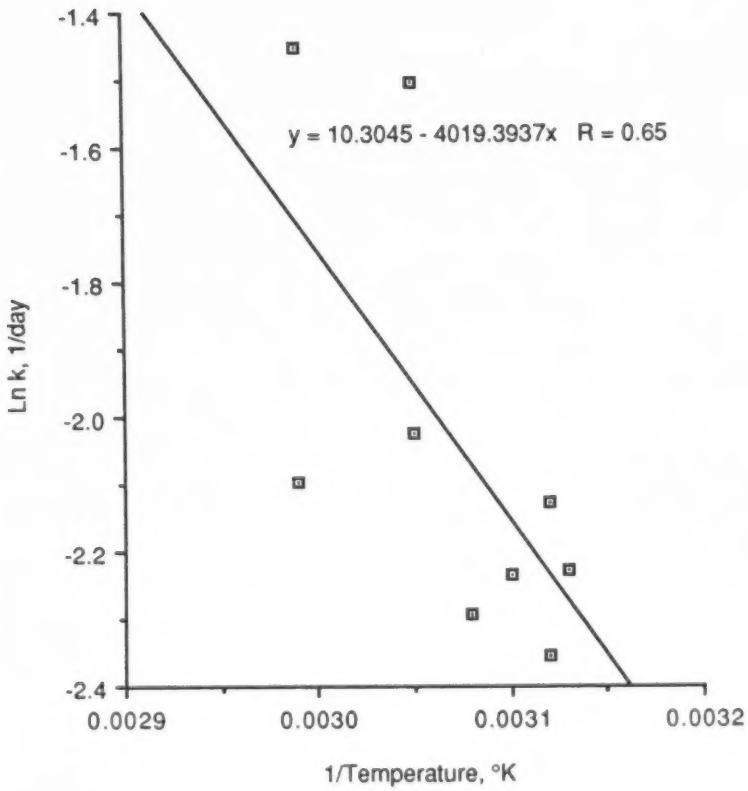

Figure 29. First-order Arrhenius plot for chemical oxygen demand from data reported by Jewell et al. (1982).

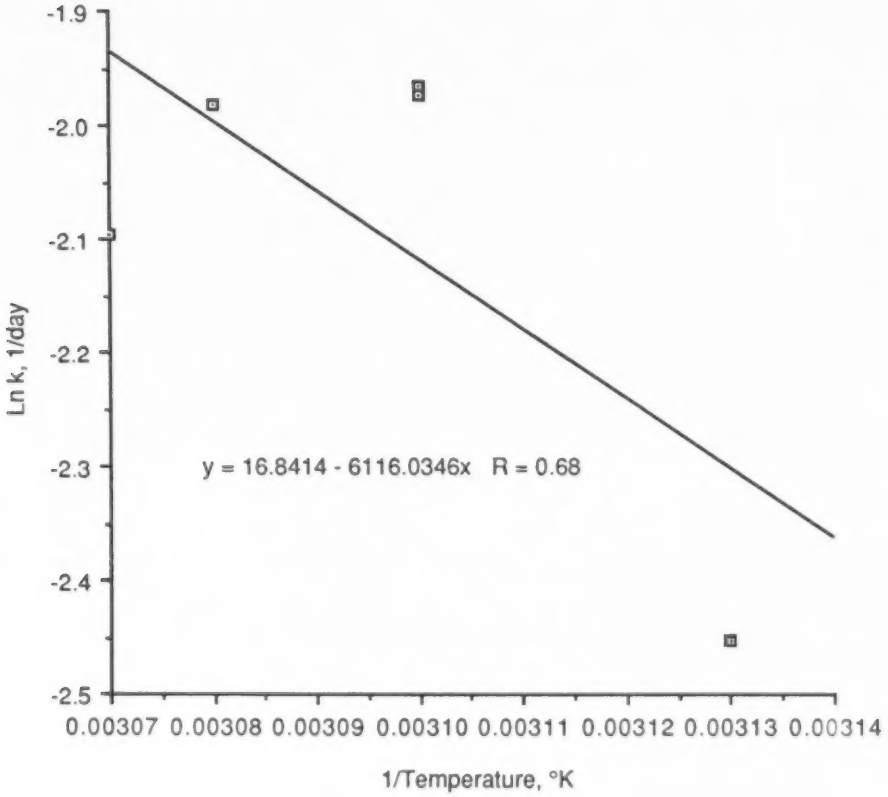

Figure 30. First-order Arrhenius plot for total volatile solids from data reported by Appleton and Venosa (1986).

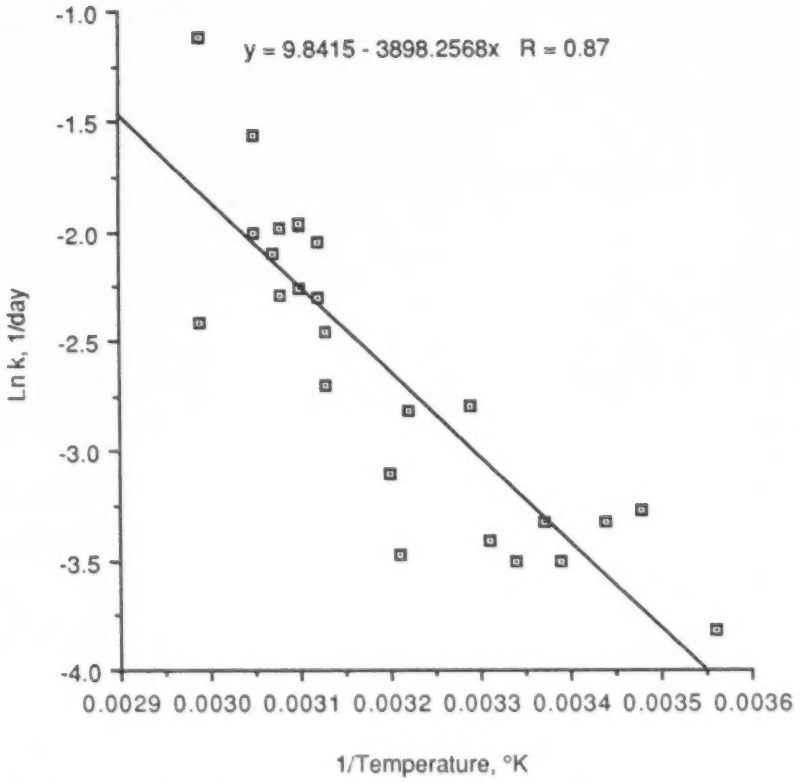

Figure 31. First-order Arrhenius plot for total volatile solids using data from this study, Jewell et al. (1982), and Appleton and Venosa (1986).

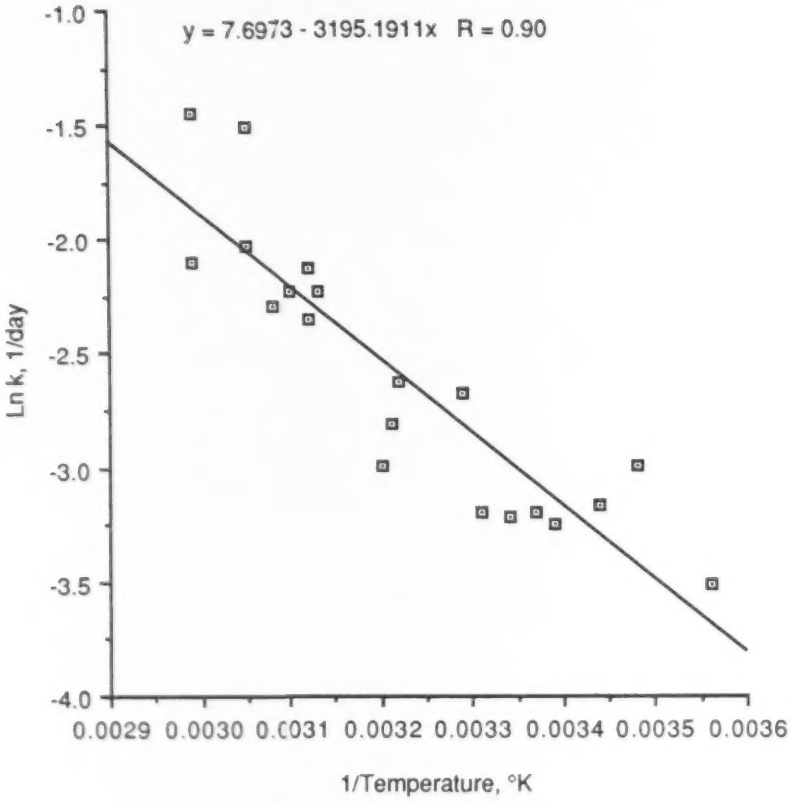

Figure 32. First-order Arrhenius plot for chemical oxygen demand using data from this study and Jewell et al. (1982).

TABLE 34. ILLUSTRATION OF THE EFFECT OF MIXED LIQUOR TEMPERATURE ON FIRST-ORDER REACTION RATE COEFFICIENTS FOR TOTAL VOLATILE SOLIDS AND CHEMICAL OXYGEN DEMAND DURING AEROBIC SLUDGE DIGESTION.

	First-order reaction rate coefficients, days $^{-1}$					
	10°C	20°C	30°C	40°C	50°C	60°C
Total volatile solids	0.020	0.031	0.049	0.073	0.108	0.155
Chemical oxygen demand	0.028	0.040	0.058	0.081	0.111	0.150

TABLE 35. ESTIMATED RESIDENCE TIMES NECESSARY TO ACHIEVE A 38 PERCENT TOTAL VOLATILE SOLIDS REDUCTION DURING AEROBIC SLUDGE DIGESTION.

Mixed liquor temperature, °C	Residence time, days
10	31
20	20
30	12
40	8
50	6
60	4

Aeration Systems Performance

Although the Framco submersible, self-aspirating aerator used in this investigation did provide the high level of oxygen transfer efficiency and thus, the reduced heat losses necessary to facilitate autoheating, the overall performance of this aeration unit was generally unsatisfactory. One continuing problem was the accumulation of various types of debris in the open area between the turbine vanes and vanes located between the two stator plates. These debris accumulations interfered with the shearing action necessary for fine bubble formation necessary for high efficiency oxygen transfer and also reduced airflow rate. Due to this problem, frequent, sometimes daily, removal and cleaning of the Framco aerator was necessary. Debris accumulations removed included hair, string, pieces of plastic tampon applicators, parts of small plastic toys, and, in one instance, a pencil.

A second problem which developed after approximately six months of Framco aerator operation was a decrease in the self-aspirated air flow rate. Initially, it was suspected by the manufacturer that this problem was the result of turbine and/or bushing wear (Figure 4). Consequently, both the turbine and the bushing were replaced in order to permit the return of the

original parts to the manufacturer for comparison with specifications. For both parts, wear was found to be minimal and replacement resulted only in a marginal increase in airflow rate. The factor or factors responsible for the failure of the Framco aerator to generate expected air flow rates were never identified even after extensive discussions with the manufacturer. One hypothesis was developed, however, which appears to provide a feasible explanation. It was theorized that the higher viscosity of sludge as compared to water reduced the upward velocity of the entrained air bubbles to the point that the aerator's pumping capacity was reduced. Since air flow rate for this aerator is a function of pumping capacity, air flow rate would then also be reduced. Why performance was satisfactory for the first six months of operation remains an unanswered question. Ultimately, this problem of low self-aspirated air flow rate was addressed by supplying the Framco aerator with a regulated, low pressure air stream. This solution permitted the realization of the study's objectives although autoheated digester operation at the residence time of five days as planned was not possible.

Due to the problems discussed above, future use of the Framco aerator for the aerobic digestion of sewage sludge can not be recommended. It is recommended, however, that other high efficiency aeration units such as the VO2 Venturi Aerator manufactured in the United Kingdom by Tom Maguire and Company, Limited be tested in the United States. It also is recommended that the development and/or testing of other high efficiency aeration devices be encouraged.

The aeration system used for the conventional aerobic digester performed as expected. It only was necessary to clean the Chicago pump diffuser coarse bubble diffusers once during 17 months of operation. These diffusers were cleaned after the first year of operation when one of the five diffusers became completely plugged. As discussed earlier, the Chicago pump diffusers were replaced with Wyss Flex-A-Tube fine bubble diffusers when the insulated cover was added to the conventional digester. It was anticipated that these diffusers would increase oxygen transfer efficiency. Such an increase as indicated by increased mixed liquor dissolved oxygen concentrations did not appear to occur, however.

Costs

Although a detailed comparison of conventional and autoheated aerobic sludge digestion costs was not one of the objectives of this investigation, it is possible to offer some general comments as to the relative costs of the two systems used in this study. The total capital cost for the autoheated digester was $16,393 as compared to a total capital cost of $11,482 for the conventional digester. This difference in total capital costs primarily was due to the higher cost, $6,275, of the autoheated digester aeration unit. The cost of the conventional digester aeration system which included a blower, diffusers, and piping was only $1,808. Tankage costs were identical and the added insulation cost for the top of the autoheated digester was only $444.

When the capital costs for the two digesters are amortized assuming no salvage value at eight percent over 20 years for tanks and insulation and over two consecutive 10 year periods for aeration equipment, the annual capital costs for the autoheated and conventional digesters are $1,572 and $860, respectively. The higher annual capital cost of the autoheated digester almost is entirely offset, however, by lower electrical energy costs. Energy requirements for the autoheated digester were only 40 kWhr per day as compared to 67 kWhr per day for the conventional digester. At $0.07 per kWhr, annual electrical energy costs for the autoheated and conventional digesters were $1,022 and $1,712, respectively. Thus, the total annual cost of the autoheated digester was $2,594 as compared to $2,572 for the conventional digester.

What is not included in the cost analysis presented above, is the impact of lower autoheated digester residence time on unit costs. Assuming the use of autoheated aerobic digestion reduces required residence time by a factor of two due to a 20°C increase in mixed liquor temperature (Table

29), a comparable reduction in unit costs will be realized. Thus, autoheated aerobic digestion of wastewater treatment sludges using air aeration is not only technically but also economically attractive.

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APPENDIX A

INFLUENT AND EFFLUENT MICROORGANISM DENSITIES

TABLE A-1. INFLUENT DENSITIES OF THE TOTAL COLIFORM, FECAL COLIFORM, AND FECAL STREPTOCOCCI GROUPS OF INDICATOR ORGANISMS AND ENTEROVIRUSES PER 100 ML BASIS.

Date	Total Coliforms*	Fecal Coliforms*	Fecal Streptococci*	Enteroviruses†
11/6/85	3.2×10^6	4.0×10^5	3.0×10^4	2720
11/11	9.0×10^7	1.5×10^6	6.5×10^4	1190
11/13	1.3×10^7	2.0×10^6	3.5×10^4	1350
11/18	1.4×10^6	1.8×10^5	4.0×10^4	1479
11/20	3.0×10^6	4.4×10^5	8.0×10^4	1328
12/2	5.0×10^6	2.6×10^5	9.0×10^4	1190
12/4	1.0×10^6	1.4×10^5	9.0×10^4	1326
1/6/86	5.5×10^6	7.0×10^5	2.2×10^4	1411
1/8	1.7×10^6	4.0×10^4	2.5×10^4	901
1/13	4.2×10^5	6.5×10^4	1.4×10^4	799
1/15	4.4×10^5	3.0×10^4	6.5×10^4	544
1/20	2.2×10^6	3.9×10^5	1.2×10^5	2244
1/22	1.0×10^6	2.4×10^5	3.5×10^4	1224
1/27	1.2×10^6	1.2×10^5	2.2×10^4	1955
1/29	1.0×10^6	3.5×10^4	1.4×10^3	850
4/9	6.0×10^6	4.5×10^4	4.9×10^3	251
4/14	3.5×10^6	1.0×10^5	4.5×10^4	137
4/16	9.0×10^5	6.0×10^4	1.5×10^4	158
4/21	2.0×10^6	9.5×10^4	1.2×10^4	368
4/23	2.5×10^6	5.7×10^4	1.6×10^4	139
4/29	1.5×10^6	3.0×10^4	1.4×10^4	217
4/30	1.5×10^6	2.0×10^4	1.8×10^4	233
5/5	1.0×10^6	4.5×10^4	2.5×10^4	232
5/12	2.0×10^6	1.0×10^5	2.4×10^4	298

(Table A-1 Continued)

Date	Total Coliforms*	Fecal Coliforms*	Fecal Streptococci*	Enteroviruses†
7/28	8.4×10^5	1.2×10^4	1.0×10^3	1088
7/30	5.2×10^5	1.0×10^4	1.5×10^4	2520
8/11	3.6×10^5	3.0×10^4	7.0×10^3	2873
8/13	2.8×10^5	3.0×10^3	8.2×10^3	2394
8/18	1.0×10^5	1.0×10^3	5.8×10^3	-
8/20	4.6×10^5	5.5×10^3	9.7×10^3	-
8/25	1.1×10^5	6.0×10^3	5.1×10^3	-
9/2	5.5×10^5	9.5×10^3	2.9×10^3	-
9/15	6.0×10^4	3.2×10^4	6.2×10^3	-
9/17	4.0×10^4	1.4×10^4	6.6×10^3	-
9/22	4.0×10^4	1.8×10^4	8.6×10^3	-
9/24	1.0×10^4	1.6×10^4	1.2×10^4	1349
9/29	5.8×10^4	1.4×10^4	1.2×10^4	1334
10/1	7.0×10^5	3.2×10^4	2.2×10^4	852
10/6	6.0×10^7	2.0×10^6	3.0×10^3	620
10/8	8.0×10^6	1.1×10^5	1.1×10^4	960
2/2/87	1.0×10^7	8.0×10^4	5.6×10^4	70
2/9	2.0×10^7	1.8×10^5	8.2×10^4	108
2/18	9.8×10^6	2.3×10^5	7.6×10^4	637
2/25	1.1×10^7	2.0×10^5	7.4×10^4	245
3/4	7.7×10^6	8.5×10^4	6.0×10^4	325
3/11	8.6×10^6	2.0×10^5	3.6×10^4	491
3/18	1.1×10^6	8.3×10^3	6.9×10^3	448
3/23	3.8×10^5	6.0×10^2	5.2×10^3	701

*Colony-forming units per 100 mL basis.
†Plaque-forming units per 100 mL basis.

TABLE A-2. INFLUENT DENSITIES OF THE TOTAL COLIFORM, FECAL COLIFORM, AND FECAL STREPTOCOCCI GROUPS OF INDICATOR ORGANISMS AND ENTEROVIRUSES PER GRAM OF TOTAL SOLIDS BASIS.

Date	Total Coliforms*	Fecal Coliforms*	Fecal Streptococci*	Enteroviruses†
11/6/85	2.7×10^6	3.4×10^5	2.5×10^4	2289
11/11	1.1×10^8	1.8×10^6	7.6×10^4	1393
11/13	1.2×10^7	1.8×10^6	3.1×10^4	1209
11/18	1.3×10^6	1.7×10^5	3.7×10^4	1368
11/20	2.5×10^6	3.7×10^5	6.6×10^4	1103
12/2	4.3×10^6	2.2×10^5	7.7×10^4	1024
12/4	7.8×10^5	1.1×10^5	7.0×10^4	1036
1/6/86	4.4×10^6	5.6×10^5	1.8×10^4	1137
1/8	1.1×10^6	2.7×10^4	1.7×10^4	604
1/13	5.2×10^5	8.0×10^4	1.7×10^4	985
1/15	5.8×10^3	3.9×10^4	8.5×10^4	712
1/20	1.1×10^6	2.0×10^5	6.1×10^4	1145
1/22	7.7×10^5	1.8×10^5	2.7×10^4	939
1/27	1.2×10^6	1.2×10^5	2.2×10^4	1880
1/29	1.5×10^6	5.3×10^4	2.1×10^3	1290
4/9	4.1×10^6	3.1×10^4	3.4×10^3	172
4/14	2.0×10^6	5.6×10^4	2.5×10^4	77
4/16	5.7×10^5	3.8×10^4	9.6×10^3	101
4/21	1.3×10^6	6.1×10^4	7.7×10^3	236
4/23	1.7×10^6	3.8×10^4	1.1×10^4	92
4/28	1.5×10^6	3.0×10^4	1.4×10^4	220
4/30	1.3×10^6	1.7×10^4	1.5×10^4	196
5/5	6.3×10^5	2.8×10^4	1.6×10^4	146
5/12	1.4×10^6	7.1×10^4	1.7×10^4	211
7/28	7.4×10^5	1.1×10^4	8.8×10^2	960
7/30	4.6×10^5	8.9×10^3	1.3×10^4	2239
8/11	3.3×10^5	2.7×10^4	6.3×10^3	2606
8/13	2.8×10^5	3.0×10^3	8.1×10^3	2371
8/18	9.6×10^4	9.6×10^2	5.6×10^3	-
8/20	4.8×10^5	5.8×10^3	1.0×10^4	-
8/25	1.2×10^5	6.6×10^3	5.6×10^3	-
9/2	4.8×10^5	1.0×10^4	3.2×10^3	-
9/15	5.7×10^4	3.0×10^4	5.9×10^3	-
9/17	5.0×10^4	1.8×10^4	8.3×10^3	-
9/22	3.3×10^4	1.5×10^4	7.0×10^3	-
9/24	9.0×10^3	1.4×10^4	1.1×10^4	1221
9/29	6.0×10^4	1.5×10^4	1.2×10^4	1389
10/1	6.4×10^5	2.9×10^4	2.0×10^4	801
10/6	8.5×10^6	1.8×10^6	2.7×10^3	525
10/8	5.8×10^6	8.0×10^4	8.0×10^3	696

(Table A-2 Continued)

Date	Total Coliforms*	Fecal Coliforms*	Fecal Streptococci*	Enteroviruses†
2/2/87	6.4×10^6	5.1×10^4	3.6×10^4	45
2/9	1.0×10^7	9.0×10^4	4.1×10^3	54
2/18	8.0×10^6	1.9×10^5	6.2×10^4	520
2/25	8.3×10^6	1.5×10^5	5.6×10^4	185
3/4	4.2×10^6	4.7×10^4	3.3×10^4	179
3/11	3.2×10^6	7.4×10^4	1.3×10^4	182
3/18	1.3×10^6	1.0×10^4	8.3×10^3	540
3/23	2.1×10^5	3.3×10^3	2.8×10^3	382

*Colony-forming units per gram of total solids basis.
†Plaque-forming units per gram of total solids basis.

TABLE A-3. AUTOHEATED DIGESTER EFFLUENT DENSITIES OF TOTAL COLIFORMS, FECAL COLIFORMS, FECAL STREPTOCOCCI, AND ENTEROVIRUSES, CFU OR PFU PER 100 ML BASIS.

Date	Total Coliforms*	Fecal Coliforms*	Fecal Streptococci*	Enteroviruses†
11/7/85	1.0×10^4	7.5×10^2	5.5×10^2	0
11/12	1.3×10^4	2.6×10^3	5.5×10^2	1
11/14	6.0×10^4	2.5×10^4	1.9×10^3	0
11/19	2.2×10^4	2.6×10^3	1.2×10^3	0
11/21	1.8×10^4	4.0×10^2	2.2×10^3	0
12/3	5.0×10^3	1.5×10^2	2.4×10^3	1
12/5	6.8×10^3	5.0×10^3	3.2×10^3	1
1/7/86	3.4×10^5	5.2×10^5	1.0×10^4	172
1/9	1.3×10^6	5.7×10^3	9.0×10^3	170
1/14	2.0×10^5	1.2×10^4	6.1×10^3	296
1/16	9.0×10^4	2.0×10^3	1.0×10^4	66
1/21	4.6×10^5	2.5×10^4	1.8×10^4	115
1/23	7.4×10^5	3.7×10^3	1.1×10^4	120
1/28	1.5×10^4	1.0×10^4	6.0×10^2	32
1/30	2.0×10^4	1.4×10^3	1.6×10^3	24
4/10	9.0×10^4	1.6×10^3	9.1×10^2	0
4/15	1.8×10^4	2.1×10^3	1.2×10^3	1
4/17	3.0×10^4	5.1×10^3	1.4×10^3	0
4/22	1.1×10^4	3.2×10^3	2.0×10^3	0
4/24	9.4×10^3	1.1×10^3	9.4×10^2	0
4/29	4.4×10^3	8.0×10^2	2.0×10^2	0
5/1	1.8×10^3	6.5×10^2	1.3×10^3	0
5/6	3.5×10^4	1.6×10^3	7.8×10^2	1
5/13	5.0×10^3	5.0×10^2	1.4×10^3	0
9/16	1.0×10^4	3.8×10^3	8.6×10^2	-
9/18	5.0×10^3	2.7×10^3	8.6×10^2	-
9/23	6.0×10^3	1.8×10^3	7.2×10^2	-
9/25	3.0×10^3	1.2×10^3	8.5×10^2	27
9/30	3.5×10^3	1.4×10^3	1.0×10^3	0
10/2	8.2×10^4	1.4×10^3	9.4×10^2	0
10/7	8.4×10^5	9.5×10^3	5.6×10^3	0
10/9	9.0×10^5	5.0×10^4	4.0×10^3	25
2/3	2.6×10^5	2.8×10^3	1.5×10^4	0
2/10	4.6×10^5	5.3×10^3	5.0×10^3	19
2/19	4.6×10^5	5.2×10^3	1.0×10^4	72
2/26	5.4×10^4	5.4×10^3	3.2×10^4	45
3/5	2.0×10^5	1.3×10^3	2.0×10^3	53
3/12	4.0×10^5	3.0×10^3	3.2×10^3	67
3/19	3.1×10^4	4.8×10^3	3.4×10^3	48
3/24	3.2×10^4	2.2×10^3	1.4×10^3	34

*Colony-forming units per 100 mL basis.

†Plaque-forming units per 100 mL basis.

TABLE A-4. AUTOHEATED DIGESTER EFFLUENT DENSITIES OF TOTAL COLIFORMS, FECAL COLIFORMS, FECAL STREPTOCOCCI, AND ENTEROVIRUSES, PER GRAM OF TOTAL SOLIDS BASIS.

Date	Total Coliforms*	Fecal Coliforms*	Fecal Streptococci*	Enteroviruses†
11/7/85	1.1×10^4	8.3×10^2	6.1×10^2	0
11/12	1.5×10^4	3.0×10^3	6.3×10^2	1
11/14	7.0×10^4	2.9×10^4	2.2×10^3	0
11/19	2.4×10^4	2.9×10^3	1.3×10^3	0
11/21	2.1×10^4	4.6×10^2	2.5×10^3	0
12/3	5.2×10^3	1.6×10^2	2.5×10^3	1
12/5	7.1×10^3	5.2×10^3	3.3×10^3	1
1/7/86	3.6×10^5	4.2×10^5	1.1×10^4	184
1/9	1.4×10^6	6.0×10^3	9.4×10^3	178
1/14	2.3×10^5	1.4×10^4	7.1×10^3	342
1/16	1.1×10^5	2.5×10^3	1.3×10^4	83
1/21	5.1×10^5	2.8×10^4	2.0×10^4	128
1/23	8.4×10^5	4.0×10^3	1.2×10^4	131
1/28	1.9×10^4	1.3×10^4	7.6×10^2	40
1/30	2.7×10^4	1.9×10^5	2.2×10^3	33
4/10	9.0×10^4	1.6×10^3	1.0×10^3	0
4/15	1.9×10^4	2.2×10^3	1.3×10^3	1
4/17	3.1×10^4	5.2×10^3	1.4×10^2	0
4/22	1.0×10^4	3.0×10^3	1.9×10^3	0
4/24	1.0×10^4	1.2×10^3	1.0×10^3	0
4/29	4.5×10^3	8.2×10^2	2.1×10^2	0
5/1	1.9×10^3	7.0×10^2	1.4×10^3	0
5/6	3.4×10^4	1.6×10^3	7.7×10^2	1
5/13	5.0×10^3	5.0×10^2	1.4×10^3	0
9/16	1.3×10^4	5.1×10^3	1.2×10^3	37
9/17	7.2×10^3	3.9×10^3	1.2×10^3	0
9/23	8.5×10^3	2.6×10^3	1.0×10^3	0
9/25	4.1×10^3	1.6×10^3	1.2×10^3	0
9/30	5.0×10^3	2.0×10^3	1.4×10^3	28
10/2	1.1×10^5	1.9×10^3	1.3×10^3	-
10/7	9.9×10^4	1.1×10^4	6.6×10^3	-
10/9	1.0×10^6	5.6×10^3	4.5×10^3	-
2/3/87	2.8×10^5	3.0×10^3	1.6×10^4	0
2/10	4.3×10^5	4.9×10^3	4.6×10^3	18
2/19	4.2×10^5	4.8×10^3	9.2×10^3	66
2/26	5.6×10^4	5.6×10^3	3.3×10^4	47
3/5	1.9×10^5	1.2×10^3	1.9×10^3	49
3/12	2.8×10^5	2.1×10^3	2.2×10^3	47
3/19	2.4×10^4	3.7×10^3	2.7×10^3	38
3/24	2.6×10^4	1.8×10^3	1.1×10^3	28

*Colony-forming units per gram of total solids.

†Plaque-forming units per gram of total solids.

TABLE A-5. CONVENTIONAL DIGESTER EFFLUENT DENSITIES OF TOTAL COLIFORMS, FECAL COLIFORMS, FECAL STREPTOCOCCI, AND ENTEROVIRUSES PER 100 ML BASIS.

Date	Total Coliforms*	Fecal Coliforms*	Fecal Streptococci*	Enteroviruses†
11/7/85	2.2×10^5	3.0×10^4	2.8×10^3	249
11/12	2.4×10^5	2.5×10^4	1.0×10^4	100
11/14	3.2×10^5	5.0×10^4	2.2×10^3	98
11/19	1.2×10^5	5.5×10^4	1.4×10^3	149
11/21	2.6×10^5	1.5×10^4	4.6×10^3	148
12/3	3.4×10^5	3.5×10^4	1.0×10^4	234
12/5	6.0×10^5	3.0×10^5	1.4×10^4	239
1/7/86	2.4×10^5	2.5×10^4	2.2×10^4	328
1/9	2.6×10^5	3.0×10^4	1.7×10^4	326
1/14	1.2×10^5	2.9×10^4	6.0×10^3	303
1/16	1.2×10^5	2.5×10^4	1.9×10^4	143
1/21	2.8×10^5	2.0×10^4	1.3×10^4	175
1/23	5.4×10^5	5.5×10^4	1.4×10^4	212
1/28	3.9×10^5	1.0×10^4	3.8×10^3	146
1/30	2.9×10^5	2.5×10^4	5.2×10^3	186
4/10	3.5×10^4	2.1×10^3	1.0×10^3	17
4/15	1.0×10^5	4.7×10^3	1.0×10^3	29
4/17	3.6×10^4	1.3×10^3	4.8×10^3	20
4/22	2.5×10^4	2.2×10^3	6.5×10^2	30
4/24	2.5×10^4	1.2×10^3	1.0×10^3	17
4/29	4.0×10^4	2.2×10^3	1.5×10^2	19
5/1	4.5×10^4	1.4×10^3	3.5×10^3	15
5/6	2.0×10^4	3.0×10^3	1.2×10^3	28
5/13	7.0×10^4	4.4×10^3	1.5×10^3	37
7/29	1.3×10^4	1.4×10^3	9.2×10^3	98
7/31	1.2×10^4	9.5×10^2	1.0×10^3	93
8/12	7.4×10^3	1.0×10^3	4.7×10^2	132
8/14	1.1×10^4	2.0×10^3	7.6×10^2	121
8/19	8.7×10^3	2.8×10^3	5.0×10^2	-
8/21	1.1×10^4	4.2×10^3	5.8×10^3	-
8/26	1.0×10^4	1.8×10^3	2.8×10^2	-
9/3	3.5×10^4	2.1×10^3	4.5×10^2	-
9/16	4.2×10^4	2.2×10^3	7.2×10^2	-
9/18	1.4×10^4	2.2×10^3	7.2×10^2	-
9/23	4.0×10^3	1.2×10^3	6.0×10^2	-
9/25	9.5×10^3	8.0×10^2	4.0×10^2	191
9/30	4.1×10^4	5.5×10^2	5.2×10^2	155
10/2	2.4×10^4	6.5×10^2	5.8×10^2	137
10/7	5.4×10^5	3.8×10^3	2.6×10^3	99
10/9	8.0×10^5	7.4×10^5	3.7×10^3	135

(Table A-5 Continued)

Date	Total Coliforms*	Fecal Coliforms	Fecal Streptococci*	Enteroviruses†
2/3/87	1.5×10^5	8.0×10^2	5.5×10^3	4
2/10	8.5×10^4	3.8×10^3	2.0×10^3	8
2/18	1.2×10^5	2.6×10^3	1.4×10^3	50
2/26	8.5×10^4	2.0×10^3	2.2×10^3	29
3/5	1.0×10^4	2.0×10^2	7.0×10^2	25
3/12	6.5×10^4	1.1×10^3	5.5×10^2	58
3/19	1.2×10^4	1.4×10^3	1.7×10^3	35
3/24	7.0×10^3	1.4×10^3	4.2×10^2	90

*Colony-forming units per 100 mL basis.
†Plaque-forming units per 100 mL basis.

TABLE A-6. CONVENTIONAL DIGESTER EFFLUENT DENSITIES OF TOTAL COLIFORMS, FECAL COLIFORMS, FECAL STREPTOCOCCI, AND ENTEROVIRUSES PER GRAM OF TOTAL SOLIDS BASIS.

Date	Total Coliforms*	Fecal Coliforms*	Fecal Streptococci*	Enteroviruses†
11/7/85	2.6×10^5	3.6×10^4	3.4×10^3	298
11/12	3.2×10^5	3.4×10^4	6.2×10^3	135
11/14	4.7×10^5	7.4×10^4	3.3×10^3	145
11/19	1.7×10^5	8.0×10^4	2.0×10^3	216
11/21	3.8×10^5	2.2×10^4	6.7×10^3	215
12/3	3.9×10^5	4.0×10^4	1.2×10^4	270
12/5	7.2×10^5	3.6×10^5	1.7×10^4	286
1/7/86	2.5×10^5	2.6×10^4	2.2×10^4	338
1/9	2.6×10^5	3.0×10^4	1.7×10^4	322
1/14	1.2×10^5	3.0×10^4	6.2×10^3	315
1/16	1.3×10^5	2.6×10^4	2.0×10^4	151
1/21	2.9×10^5	2.1×10^4	1.3×10^4	180
1/23	5.9×10^5	6.0×10^4	1.5×10^4	231
1/28	4.6×10^5	1.2×10^4	4.5×10^3	174
1/30	3.5×10^5	3.0×10^4	6.3×10^3	227
4/10	3.5×10^4	2.4×10^3	1.2×10^3	20
4/15	1.1×10^5	5.1×10^3	1.1×10^3	31
4/17	4.1×10^4	1.5×10^3	5.4×10^3	23
4/22	2.6×10^4	2.3×10^3	6.9×10^2	32
4/24	2.6×10^4	1.3×10^3	1.0×10^3	18
4/29	4.3×10^4	2.4×10^3	1.6×10^2	20
5/1	5.1×10^4	1.6×10^3	4.0×10^3	17
5/6	2.0×10^4	3.0×10^3	1.2×10^3	28
5/13	7.1×10^4	4.5×10^3	1.5×10^3	38
7/29	1.6×10^4	1.7×10^3	1.1×10^3	118
7/31	1.5×10^4	1.2×10^3	1.2×10^3	113
8/12	8.4×10^3	1.1×10^3	5.4×10^2	150
8/14	1.3×10^4	2.3×10^3	7.8×10^2	138
8/19	1.0×10^4	3.3×10^3	5.9×10^2	-
8/21	1.3×10^4	5.1×10^3	7.1×10^3	-
8/26	1.2×10^4	2.2×10^3	3.4×10^2	-
9/3	4.4×10^4	2.6×10^3	5.7×10^2	-
9/16	5.5×10^4	2.9×10^3	9.4×10^2	-
9/18	1.8×10^4	2.8×10^3	9.2×10^2	-
9/23	5.1×10^3	1.5×10^3	7.6×10^2	-
9/25	1.2×10^4	1.0×10^3	5.1×10^2	242
9/30	5.5×10^4	7.5×10^2	7.0×10^2	210
10/2	3.0×10^4	8.2×10^2	7.3×10^2	172
10/7	7.8×10^5	5.5×10^3	3.7×10^3	142
10/9	1.1×10^6	9.8×10^5	4.9×10^3	179

(Table A-6 Continued)

Date	Total Coliforms*	Fecal Coliforms*	Fecal Streptococci*	Enteroviruses†
2/3/87	1.6×10^4	8.4×10^2	5.8×10^3	4
2/10	8.3×10^4	3.7×10^3	2.0×10^3	8
2/19	1.3×10^5	2.7×10^3	1.5×10^3	52
2/26	9.0×10^4	2.1×10^3	2.3×10^3	31
3/5	1.0×10^4	2.0×10^2	7.1×10^2	25
3/12	5.2×10^4	8.7×10^2	4.4×10^2	46
3/19	1.0×10^4	1.2×10^3	1.4×10^3	30
3/24	6.0×10^3	1.1×10^3	3.4×10^2	78

*Colony-forming units per gram of total solids.
†Plaque-forming units per gram of total solids.

APPENDIX B

COMPARISONS OF INFLUENT AND EFFLUENT MICROORGANISM DENSITIES

TABLE B-1. COMPARISONS OF INFLUENT AND EFFLUENT DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES FOR THE SAMPLING PERIOD 6 NOVEMBER - 5 DECEMBER 1985.

	Log_{10} CFU/G TS* Mean ± Standard Deviation		
	Influent	Effluent 20 days, 15°C	Effluent 20 days, 38°C
Total coliforms	$6.52^{a\dagger} \pm 0.84$	$5.41^{b} \pm 0.48$	$4.14^{c} \pm 0.28$
Fecal coliforms	$5.47^{a} \pm 0.39$	$4.76^{b} \pm 0.40$	$3.27^{c} \pm 0.75$
Fecal streptococci	$4.71^{a} \pm 0.19$	$3.85^{b} \pm 0.45$	$3.19^{c} \pm 0.30$
Enteroviruses¥	$3.11^{a} \pm 0.11$	$2.33^{b} \pm 0.13$	$0.00^{c} \pm 0.00$

*Colony-forming units per gram of total solids.
†Means in the same row with a common superscript are not significantly different (P<0.05).
¥Plaque-forming units.

TABLE B-2. COMPARISONS OF INFLUENT AND EFFLUENT DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES FOR THE SAMPLING PERIOD 6 JANUARY - 30 JANUARY 1986.

	Log_{10} CFU/G TS* Mean ± Standard Deviation		
	Influent	Effluent 20 days, 8°C	Effluent 10 days, 31°C
Total coliforms	$6.06^{a\dagger} \pm 0.29$	$5.43^{b} \pm 0.24$	$5.31^{b} \pm 0.68$
Fecal coliforms	$5.00^{a} \pm 0.43$	$4.32^{b} \pm 0.30$	$4.06^{b} \pm 0.79$
Fecal streptococci	$4.21^{a} \pm 0.41$	$4.05^{b} \pm 0.27$	$3.84^{b} \pm 0.48$
Enteroviruses¥	$3.01^{a} \pm 0.15$	$2.37^{b} \pm 0.13$	$2.04^{c} \pm 0.34$

*Colony-forming units per gram of total solids.
†Means in the same row with a common superscript are not significantly different (P<0.05).
¥Plaque-forming units.

TABLE B-3. COMPARISONS OF INFLUENT AND EFFLUENT DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES FOR THE SAMPLING PERIOD 9 APRIL - 13 MAY 1986.

	Log_{10} CFU/G TS* Mean ± Standard Deviation		
	Influent	Effluent 20 days, 18°C	Effluent 15 days, 40°C
Total coliforms	$5.91^{a\dagger}$ ± 0.26	4.58^{b} ± 0.27	4.07^{c} ± 0.51
Fecal coliforms	4.41^{a} ± 0.39	3.46^{b} ± 0.31	3.17^{b} ± 0.32
Fecal streptococci	3.98^{a} ± 0.21	2.90^{b} ± 0.56	2.79^{b} ± 0.51
Enteroviruses¥	2.17^{a} ± 0.18	1.39^{b} ± 0.12	0.03^{c} ± 0.10

*Colony-forming units per gram of total solids.
†Means in the same row with a common superscript are not significantly different (P<0.05).
¥Plaque-forming units.

TABLE B-4. COMPARISONS OF INFLUENT AND EFFLUENT DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES FOR THE SAMPLING PERIOD 28 JULY - 3 SEPTEMBER 1986.

	Log_{10} CFU/G TS* Mean ± Standard Deviation	
	Influent	Effluent 20 days, 26°C
Total coliforms	$5.49^{a\dagger}$ ± 0.31	4.16^{b} ± 0.22
Fecal coliforms	3.81^{a} ± 0.43	3.34^{b} ± 0.22
Fecal streptococci	3.72^{a} ± 0.36	2.96^{b} ± 0.40
Enteroviruses¥	3.28^{a} ± 0.20	2.11^{b} ± 0.06

*Colony-forming units per gram of total solids.
†Means in the same row with a common superscript are not significantly different (P<0.05).
¥Plaque-forming units.

TABLE B-5. COMPARISONS OF INFLUENT AND EFFLUENT DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES FOR THE SAMPLING PERIOD 5 SEPTEMBER - 9 OCTOBER 1986.

	Log_{10} CFU/G TS* Mean ± Standard Deviation		
	Influent	Effluent 20 days, 22°C	Effluent 10 days, 38°C
Total coliforms	$5.57^{a\dagger}$ ± 0.91	4.38^{b} ± 1.08	4.42^{b} ± 0.86
Fecal coliforms	4.41^{a} ± 0.27	3.45^{b} ± 0.69	3.57^{b} ± 0.33
Fecal streptococci	4.07^{a} ± 0.29	3.06^{b} ± 0.36	3.25^{b} ± 0.31
Enteroviruses¥	2.94^{a} ± 0.17	2.27^{b} ± 0.09	0.60^{c} ± 0.83

*Colony-forming units per gram of total solids.
†Means in the same row with a common superscript are not significantly different (P<0.05).
¥Plaque-forming units.

TABLE B-6. COMPARISONS OF INFLUENT AND EFFLUENT DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES FOR THE SAMPLING PERIOD 2 FEBRUARY - 26 MARCH 1987.

	Log_{10} CFU/G TS* Mean ± Standard Deviation		
	Influent	Effluent 20 days, 24°C	Effluent 15 days, 29°C
Total coliforms	$6.52^{a\dagger}$ ± 0.56	4.46^{b} ± 0.52	5.12^{c} ± 0.53
Fecal coliforms	4.65^{a} ± 0.60	3.08^{b} ± 0.39	3.48^{b} ± 0.24
Fecal streptococci	4.34^{a} ± 0.47	3.10^{b} ± 0.41	3.68^{c} ± 0.51
Enteroviruses¥	2.27^{a} ± 0.41	1.39^{b} ± 0.40	1.39^{b} ± 0.59

*Colony-forming units per gram of total solids.
†Means in the same row with a common superscript are not significantly different (P<0.05).
¥Plaque-forming units.

TABLE B-7. SUMMARY OF OBSERVED REDUCTIONS IN THE GEOMETRIC MEAN DENSITIES OF INDICATOR ORGANISMS AND ENTEROVIRUSES.

Sampling period	Digester	Log_{10} Reduction, CFU/G TS*			
		Total coliforms	Fecal coliforms	Fecal streptococci	Enteroviruses†
11/6 - 12/5/85	Conventional	1.22 ± 0.76	0.71 ± 0.62	0.86 ± 0.32	0.78 ± 0.17
	Autoheated	2.39 ± 0.81	2.20 ± 0.69	1.55 ± 0.26	3.11 ± 0.12
1/6 - 1/30/86	Conventional	0.63 ± 0.31	0.69 ± 0.49	0.16 ± 0.40	0.64 ± 0.23
	Autoheated	0.74 ± 0.73	0.94 ± 0.51	0.35 ± 0.47	0.97 ± 0.44
4/9 - 5/13/86	Conventional	1.33 ± 0.23	0.95 ± 0.32	0.96 ± 0.33	0.79 ± 0.21
	Autoheated	1.84 ± 0.55	1.24 ± 0.57	1.19 ± 0.48	2.14 ± 0.19
7/28 - 9/3/86	Conventional	1.34 ± 0.29	0.47 ± 0.59	0.76 ± 0.48	1.17 ± 0.18
9/15 - 10/9/86	Conventional	1.05 ± 0.55	0.84 ± 0.17	0.82 ± 0.27	0.67 ± 0.10
	Autoheated	0.98 ± 0.32	0.96 ± 0.48	1.01 ± 0.38	2.34 ± 0.81
2/2 - 3/26/87	Conventional	2.06 ± 0.36	1.57 ± 0.57	1.24 ± 0.34	0.88 ± 0.21
	Autoheated	1.40 ± 0.37	1.17 ± 0.50	0.66 ± 0.32	0.88 ± 0.41

*Colony-forming units per gram of total solids.
†Plaque-forming units per gram of total solids.

APPENDIX C

INFLUENT AND EFFLUENT PHYSICAL AND CHEMICAL CHARACTERISTICS

TABLE C-1. AUTOHEATED DIGESTER INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE SAMPLING PERIOD 6 NOVEMBER - 5 DECEMBER 1985.

	Concentration, g/L							
	Total Solids		Total Volatile Solids		Chemical Oxygen Demand		Organic Nitrogen	
Date	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
11/6 - 7/85	13.215	9.038	9.583	5.730	15.985	6.221	0.871	0.340
11/11 - 12	12.242	8.692	8.784	5.508	14.351	5.928	0.791	0.257
11/13 - 14	12.179	8.557	8.785	5.425	14.206	6.298	0.781	0.328
11/18 - 19	12.032	9.063	8.664	5.807	13.973	6.384	0.747	0.342
11/20 - 21	12.114	8.717	8.699	5.195	13.955	6.460	0.745	0.349
11/25 - 26	12.454	9.528	8.945	5.600	14.356	7.142	0.769	0.377
12/2 - 3	12.575	9.640	9.095	5.532	14.702	7.812	0.788	0.398
12/4-5	12.718	9.612	9.228	5.450	14.900	7.144	0.798	0.409
$\bar{X}$	12.441	9.106	8.973	5.531	14.555	6.674	0.786	0.350
SD	0.392	0.439	0.315	0.190	0.664	0.629	0.039	0.048

TABLE C-2. CONVENTIONAL DIGESTER INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE SAMPLING PERIOD 6 NOVEMBER - 5 DECEMBER 1985.

	Concentration, g/L							
	Total Solids		Total Volatile Solids		Chemical Oxygen Demand		Organic Nitrogen	
Date	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
11/6 - 7/85	12.539	8.352	9.583	5.492	15.985	7.910	0.876	0.505
11/11 - 12	11.545	7.418	8.784	4.690	14.351	6.536	0.791	0.398
11/13 - 14	11.474	6.755	8.785	4.467	14.206	6.374	0.781	0.370
11/18 - 19	11.335	6.887	8.664	4.663	13.973	6.536	0.747	0.390
11/20 - 21	11.409	6.885	8.699	4.623	13.955	7.068	0.745	0.377
11/25 - 26	11.757	7.627	8.945	5.213	14.356	7.142	0.769	0.408
12/2 - 3	11.878	8.653	9.095	6.095	14.702	8.258	0.788	0.469
12/4-5	12.013	7.617	9.228	5.853	14.900	8.740	0.798	0.529
$\bar{X}$	11.744	7.617	8.973	5.035	14.555	7.320	0.786	0.431
SD	0.399	0.758	0.315	0.594	0.604	0.883	0.039	0.061

TABLE C-3. AUTOHEATED DIGESTER INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE SAMPLING PERIOD 6 JANUARY - 30 JANUARY 1986.

	Concentration, g/L							
	Total Solids		Total Volatile Solids		Chemical Oxygen Demand		Organic Nitrogen	
Date	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
1/6 - 7/86	12.452	9.340	10.049	6.635	16.275	9.728	0.887	0.583
1/8 - 9	13.029	9.565	10.556	6.948	16.944	10.528	0.919	0.657
1/13 - 14	12.068	8.650	9.775	6.365	15.760	10.032	0.855	0.604
1/15 - 16	11.073	7.913	8.901	5.648	14.182	8.588	0.782	0.531
1/20 - 21	13.144	9.005	10.502	6.530	16.387	9.896	0.880	0.577
1/22 - 23	13.121	9.163	10.193	6.360	15.705	9.907	0.829	0.605
1/27 - 28	12.181	7.920	9.335	5.315	14.498	7.600	0.736	0.470
1/29-30	10.975	7.327	8.379	4.830	13.071	7.068	0.665	0.428
$\bar{X}$	12.255	8.610	9.711	6.079	15.353	9.168	0.819	0.557
SD	0.866	0.803	0.780	0.733	1.312	1.264	0.086	0.076

TABLE C-4. CONVENTIONAL DIGESTER INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE SAMPLING PERIOD 6 JANUARY - 30 JANUARY 1986.

	Concentration, g/L							
	Total Solids		Total Volatile Solids		Chemical Oxygen Demand		Organic Nitrogen	
Date	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
1/6 - 7/86	12.559	9.695	10.022	7.228	16.153	9.500	0.883	0.634
1/8 - 9	12.902	10.138	10.340	7.625	16.593	10.452	0.904	0.682
1/13 - 14	12.468	9.625	10.016	7.232	16.134	10.868	0.879	0.658
1/15 - 16	11.860	9.447	9.496	6.988	15.204	10.108	0.835	0.544
1/20 - 21	12.847	9.718	10.293	7.104	16.272	10.292	0.882	0.624
1/22 - 23	12.886	9.172	10.142	6.635	15.891	9.984	0.852	0.582
1/27 - 28	12.382	8.393	9.464	5.938	15.125	8.740	0.793	0.530
1/29-30	11.683	8.193	9.074	5.857	14.251	8.436	0.746	0.558
$\bar{X}$	12.448	9.298	9.856	6.826	15.703	9.798	0.847	0.602
SD	0.464	0.679	0.456	0.636	0.777	0.846	0.054	0.056

TABLE C-5. AUTOHEATED DIGESTER INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE SAMPLING PERIOD 9 APRIL - 13 MAY 1986.

	Concentration, g/L							
	Total Solids		Total Volatile Solids		Chemical Oxygen Demand		Organic Nitrogen	
Date	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
4/9 - 10/86	13.289	9.143	10.764	6.737	16.457	9.821	0.884	0.601
4/14 - 15	14.912	9.590	12.130	7.097	18.510	10.076	0.984	0.654
4/16 - 17	15.045	9.718	12.236	7.180	18.847	11.374	0.988	0.614
4/21 - 22	15.866	10.515	12.738	7.793	20.107	15.996	1.040	0.634
4/23 - 24	15.742	9.365	12.550	6.737	19.897	9.853	1.027	0.578
4/28 - 29	14.851	9.737	11.755	6.877	18.893	9.598	0.990	0.585
4/30 - 5/1	14.374	9.273	13.374	6.545	18.272	10.192	0.967	0.574
5/5 - 6	14.803	10.155	11.698	7.237	18.781	10.166	1.006	0.603
5/7 - 8	14.313	9.812	11.339	6.992	18.147	10.243	0.972	0.617
5/12 - 13	13.941	10.003	11.039	7.150	17.621	10.488	0.956	0.614
$\bar{X}$	14.714	9.731	11.962	7.034	18.553	10.781	0.981	0.607
SD	0.739	0.398	0.764	0.331	0.999	1.798	0.041	0.237

TABLE C-6. CONVENTIONAL DIGESTER INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE SAMPLING PERIOD 9 APRIL - 13 MAY 1986.

	Concentration, g/L							
	Total Solids		Total Volatile Solids		Chemical Oxygen Demand		Organic Nitrogen	
Date	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
4/9 - 10/86	12.564	8.668	10.145	6.075	15.533	8.538	0.826	0.460
4/14 - 15	13.752	9.252	11.155	6.540	17.008	9.174	0.900	0.530
4/16 - 17	14.000	8.880	11.359	6.368	17.445	9.424	0.914	0.516
4/21 - 22	14.745	9.445	11.838	6.678	18.553	10.490	0.960	0.579
4/23 - 24	14.830	9.558	11.845	6.763	18.645	10.004	0.963	0.558
4/28 - 29	14.338	9.333	11.432	6.415	18.204	9.374	0.949	0.529
4/30 - 5/1	14.135	8.835	11.225	6.222	17.885	9.448	0.940	0.515
5/5 - 6	14.482	9.850	11.493	6.895	18.307	9.778	0.974	0.572
5/7 - 8	14.192	9.565	11.277	6.760	17.938	10.010	0.955	0.576
5/12 - 13	14.056	9.843	11.169	6.848	17.739	10.564	0.955	0.570
$\bar{X}$	14.109	9.323	11.294	6.556	17.726	9.680	0.934	0.540
SD	0.604	0.394	0.450	0.264	0.870	0.586	0.042	0.036

TABLE C-7. CONVENTIONAL DIGESTER INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE SAMPLING PERIOD 28 JULY - 3 SEPTEMBER 1986.

	Concentration, g/L							
	Total Solids		Total Volatile Solids		Chemical Oxygen Demand		Organic Nitrogen	
Date	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
7/28 - 29	11.893	8.295	9.022	5.168	14.618	7.440	0.817	0.432
7/30 - 31	11.808	8.230	8.945	5.272	14.563	7.216	0.817	0.433
8/4 - 5	11.765	8.758	8.942	5.620	14.457	7.372	0.811	0.456
8/8 - 9	11.862	8.720	9.027	5.630	14.563	7.220	0.821	0.456
8/11 - 12	11.820	8.777	8.996	5.700	14.437	7.670	0.826	0.471
8/13 - 14	11.598	8.753	8.837	5.702	14.133	7.595	0.815	0.470
8/18 - 19	11.309	8.460	8.611	5.588	13.790	7.634	0.801	0.428
8/20 - 21	11.074	8.158	8.444	5.335	13.371	7.320	0.788	0.436
8/25 - 26	10.605	8.165	8.058	5.175	12.725	8.500	0.770	0.416
8/27 - 28	10.399	7.600	7.913	5.090	12.433	8.492	0.757	0.380
9/2 - 3	10.554	7.938	8.102	5.490	12.829	8.745	0.775	0.375
$\bar{X}$	11.335	8.350	8.627	5.434	13.811	7.746	0.800	0.432
SD	0.555	0.367	0.409	0.220	0.794	0.534	0.022	0.031

TABLE C-8. AUTOHEATED DIGESTER INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE SAMPLING PERIOD 15 SEPTEMBER - 9 OCTOBER 1986.

	Concentration, g/L							
	Total Solids		Total Volatile Solids		Chemical Oxygen Demand		Organic Nitrogen	
Date	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
9/15 - 16	9.963	7.463	7.598	5.162	10.827	5.382	0.698	0.367
9/17 - 18	9.513	6.930	7.324	4.717	10.210	5.105	0.666	0.317
9/22 - 23	10.332	7.043	8.103	4.905	10.355	5.303	0.679	0.304
9/24 - 25	10.492	7.278	8.282	5.202	11.545	7.396	0.692	0.392
9/29 - 30	10.146	7.043	7.987	4.972	11.653	8.030	0.698	0.408
10/3 - 4	11.253	7.368	8.965	4.775	13.029	7.878	0.819	0.411
10/6 - 7	11.372	8.475	8.971	5.942	13.227	8.593	0.805	0.506
10/8 - 9	11.893	8.877	9.356	6.072	13.736	8.289	0.838	0.503
$\bar{X}$	10.620	7.560	8.323	5.218	11.823	6.997	0.737	0.401
SD	0.808	0.720	0.716	0.516	1.360	1.477	0.071	0.075

TABLE C-9. CONVENTIONAL DIGESTER INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE SAMPLING PERIOD 15 SEPTEMBER - 9 OCTOBER 1986.

	Concentration, g/L							
	Total Solids		Total Volatile Solids		Chemical Oxygen Demand		Organic Nitrogen	
Date	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
9/15 - 16	10.229	7.645	7.809	5.028	11.658	5.382	0.730	0.366
9/17 - 18	9.962	7.785	7.642	5.333	11.224	6.014	0.710	0.369
9/22 - 23	10.300	7.908	7.996	5.525	11.060	6.666	0.707	0.380
9/24 - 25	10.381	7.890	8.101	5.638	11.602	6.792	0.710	0.372
9/29 - 30	10.191	7.372	7.961	5.090	11.635	6.840	0.710	0.404
10/3 - 4	10.802	7.943	8.516	4.955	12.414	6.590	0.775	0.408
10/6 - 7	10.898	6.957	8.560	4.573	12.561	7.300	0.772	0.395
10/8 - 9	11.228	7.542	8.812	4.927	12.902	7.985	0.793	0.409
$\bar{X}$	10.499	7.630	8.175	5.134	11.882	6.696	0.738	0.388
SD	0.430	0.337	0.409	0.348	0.664	0.780	0.036	0.018

TABLE C-10. AUTOHEATED DIGESTER INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE SAMPLING PERIOD 2 FEBRUARY - 26 MARCH 1987.

	Concentration, g/L							
	Total Solids		Total Volatile Solids		Chemical Oxygen Demand		Organic Nitrogen	
Date	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
2/2-3/87	13.020	9.368	10.263	6.535	15.958	9.542	0.879	0.554
2/4 -5	13.512	9.840	10.659	6.962	16.563	9.466	0.901	0.591
2/9 - 10	14.960	10.815	11.792	7.507	18.390	10.586	0.996	0.594
2/11 - 12	14.742	11.125	11.561	7.795	18.023	9.962	0.987	0.617
2/16 - 17	14.739	10.603	11.607	7.707	18.049	10.335	0.991	0.673
2/18 - 19	14.379	10.917	11.384	7.763	17.732	11.742	0.984	0.714
2/23 - 24	14.009	10.155	11.086	7.215	17.032	10.60	0.970	0.683
2/25 - 26	13.887	9.635	11.018	6.968	16.796	10.570	0.963	0.638
3/2 - 3	13.972	10.372	11.083	7.292	17.043	10.827	0.976	0.671
3/4 - 5	14.623	10.798	11.452	7.708	17.417	11.429	0.996	0.644
3/9 - 10	17.425	13.038	13.178	9.022	20.505	13.308	1.201	0.799
3/11 - 12	18.915	14.238	14.102	9.997	21.285	14.753	1.256	0.878
3/16 - 17	18.560	14.018	13.772	9.598	20.834	13.232	1.170	0.809
3/18 - 19	17.026	12.770	12.613	7.692	19.118	11.060	1.070	0.624
3/23 - 24	16.507	12.342	12.293	8.518	18.725	11.642	0.992	0.738
3/25 - 26	16.217	12.758	12.093	8.493	18.671	11.472	0.972	0.742
$\bar{X}$	15.406	1.424	11.872	7.923	18.259	11.283	1.019	0.686
SD	1.753	1.503	1.051	0.936	1.507	1.393	0.101	0.086

TABLE C-11. CONVENTIONAL DIGESTER* INFLUENT AND EFFLUENT CHARACTERISTICS FOR THE SAMPLING PERIOD 2 FEBRUARY - 26 MARCH 1987.

	Concentration, g/L							
	Total Solids		Total Volatile Solids		Chemical Oxygen Demand		Organic Nitrogen	
Date	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
2/2-3/87	12.926	9.553	10.183	6.010	15.847	8.091	0.882	0.507
2/4 -5	13.302	10.257	10.486	6.415	16.296	8.397	0.897	0.544
2/9 - 10	14.428	10.253	11.372	6.467	17.716	8.544	0.967	0.506
2/11 - 12	14.314	10.162	11.235	6.295	17.502	9.434	0.964	0.531
2/16 - 17	14.398	9.967	11.337	6.385	17.634	9.294	0.972	0.460
2/18 - 19	14.165	9.577	11.201	6.242	17.453	9.167	0.970	0.522
2/23 - 24	13.958	9.475	11.035	5.935	16.992	9.699	0.962	0.487
2/25 - 26	13.888	9.437	11.005	6.282	16.847	8.745	0.958	0.550
3/2 - 3	13.957	9.480	11.065	6.067	17.033	9.398	0.969	0.502
3/4 - 5	14.454	9.832	11.346	6.273	17.315	10.902	0.985	0.495
3/9 - 10	16.658	10.965	12.706	6.860	19.749	10.570	1.146	0.559
3/11 - 12	17.863	12.580	13.450	8.307	20.396	11.483	1.192	0.740
3/16 - 17	17.820	12.598	13.337	8.087	20.236	10.114	1.139	0.779
3/18 - 19	16.726	11.775	12.497	7.692	18.989	12.500	1.066	0.774
3/23 - 24	16.382	11.608	12.267	7.803	18.695	12.165	1.006	0.628
3/25 - 26	16.208	12.013	12.140	7.615	18.695	10.339	0.991	0.619
$\bar{X}$	15.090	10.596	11.666	6.796	17.962	9.928	1.004	0.575
SD	1.538	1.115	0.929	0.785	1.317	1.279	0.085	0.101

*With insulated cover.